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CONCEPT OF A SYNERGETIC AIR-BREATHING ENGINE FOR HYPERSONIC FLIGHT

Final Report

Contract F61708-96-W0304

Abstract

The report describes the last versions of the synergetic air-breathing jet engine allowing the acceleration of a hypersonic vehicle over a Mach number range of M = 0 - 5.5 to be carried out more effectively under current technological limitations than with using the known engine types. The aerothermodynamic performance of 20 versions of the synergetic engine are presented which are calculated on the basis of the real-gas model, the optimum one was selected among them. Estimates of the fuel burn for vehicle acceleration with the engine version close to the optimum one as well as of the structures masses of the two versions were conducted. High promising advantages of the synergetic engine are shown and the problems are revealed of its integration with the air intake of a vehicle, and the engine version is described where the problems are solved. According to estimates, the gain from employing this'engine is obtained to be no less than 2.5 % of the start mass of a vehicle. A program aimed at further studies to develop the proposed power plant concept is presented.

1. Introduction

In the preceding report under the present contract [1] two fundamental technological problems were revealed which do not allow there-described layout of the hypersonic synergetic air-breathing engine SJ-2 to be practically designed. The first problem is associated with the blade height of the first stages of the primary vapor turbine. To solve the problem, the version SJ-3 of the power plant was developed which was described in the second section of the present report. Then the second fundamental technological problem is analyzed, the problem of matching the characteristics of the frontal compressor of the hypersonic synergetic engine with those of the bladed units of its inverse-cycle module followed by the description of the engine version SJ-4 which allows solving this problem with taking into account the necessity of integrating the engine with a vehicle air intake. In the next, fourth section a new variant of the primary hydrogen module of the engine is described where all possible resources are used to enhance thrust and economic characteristics of the power plant (engine version SJ-5). This is followed by the presentation of the first results of integrating the synergetic engine with the air intake of a hypersonic vehicle. The sixth section of the report contains the estimates for the structural masses of the basic components and the entire engine of the layout being considered. When considering all the characteristics of the synergetic power plant, estimated in parallel for the same conditions were the analogous parameters of the turbo-expander engine with the compressor pressure ratio $\pi_c^\circ = 3.5$ at $M = 0$ which is the version close to the optimum one, and all conclusions were made on the basis of the comparative analysis of these two types of power plants.

The main result of the present report is the substantiation of the advanced technology level of the synergetic air-breathing jet engine as applied to the acceleration of hypersonic vehicles. But for the engine characteristics to be better matched with those of the other vehicle components, first of all, the air intake, the necessity was revealed to further develop the layout of the synergetic engine up to the version SJ-6 which would allow the potentialities of the synergetic concept to be implemented in real conditions of integrating basic subsystems of a hypersonic vehicle. In addition, the analysis of the results obtained allows one to state that, if used as a generator unit, the synergetic module of the type being considered, permits the layouts of gas-turbine engines of practically any purpose to be developed which would have performance higher than those of currently known layouts of liquid hydrogen-fueled gas-turbine power plants. Because of this, proposed in the last, seventh section is the program both for further search for optimum versions of the hypersonic synergetic air-breathing power plant and for preliminary conceptual studies of air-breathing engines to be serviceable under different flight conditions as well as for some versions of different gas-turbine power plants.

2. Solution to the first fundamental technological problem of creating a synergetic engine: the version SJ-3

In the preceding report [1], the version SJ-2 of the synergetic air-breathing engine was described which allows in principle obtaining throughout the acceleration trajectory of a hypersonic vehicle the thrust and economic characteristics which are significantly better than those of the turbo-expander engine in similar conditions. But subsequent investigations have shown that the current technology level does not allow the synergetic engine of such a type to be practically designed. First of all, this is associated with the blade height of the first stages of the primary vapor turbine, which, as a rule, is a problem even for turbo-expander power plant operating in less severe conditions [2]. If there is no a gearbox between this turbine and the frontal compressor, the diameter of the vapor turbine must be commensurable with the compressor diameter for the turbine to have a reasonable number of stages (no more than 15 - 20). As is known, the stoichiometric hydrogen flow is about 2.9 % of the air flow, the hydrogen pressure p_t at the turbine entry at low Mach numbers must be no less than 150 - 300 times greater than the air pressure at the frontal compressor entry [1] for the fuel to be injected and atomized in all the combustion chambers of the synergetic engine. Under these conditions the height of the open-flow area of the primary vapor turbine which defines the blade height h of its first stage at typical start thrust values of $P_o = 250 - 300$ kN becomes an order of magnitude less than the minimum value $h^* = 10$ mm allowable from technological considerations. The implication is that for the version SJ-2 of the power plant considered the minimum allowable thrust level is 100 times greater than that practically needed ($P_o^* \sim p_t^2$ at $h = \text{const}$). At an engine thrust of 300 kN and a blade height of 10 mm of the turbine first stage the maximum allowable pressure at its entry will be about $p_t^* = 2$ MPa while the pressure levels needed for the versions SJ-2-30 ÷ SJ-2-15 of the synergetic engine make up 16 - 27 MPa [1].

The employment of a gearbox allows significantly reducing the vapor turbine diameter and resolving this contradiction but at the indicated thrust levels ($P_o = 250 - 300$ kN) gearbox power is of so high magnitude (up to 50 MW) that are unattainable with current-technology gearbox designs. The fact that the turbine power of the

engine version SJ-2 is divided between the frontal and booster compressors somewhat improves matters in principle, but the presence of two gearboxes complicates the engine design to such an extent that the practical implementation of the engine layout would be at least rather problematical.

This technological problem was solved with the employment of a complex of elements situated in the fuel line of the synergetic air-breathing engine thus allowing the performance of the units located both in the gas passage and in the fuel line of the power plant to be matched [3-5]. This complex of elements is for short called synergizer. Its employment makes it possible to create a real-world synergetic air-breathing engine.

In Russian and American patent applications [3-5], three variants of the synergizer have consecutively been presented. The subsequent analysis has shown that the potentially most effective are the second and third versions, so only they are described in the present report.

Fig. 1 shows the second synergizer version and Fig. 2(a) shows the synergetic air-breathing engine (version SJ-3) where all the elements of the fuel line located outside the gas passage of the power plant are replaced by the synergizer which is labeled S in Fig. 2. In this primary hydrogen unit of the synergetic engine such fuel system elements previously described in report [1] as three controllable valves denoted with indices 1, 2 and 3, pump 14, heat exchanger-regenerator 15 and auxiliary vapor turbine 18 with shaft 19 for driving the pump are supplemented by fuel-line-located so-called frontal vapor turbine 23, recovery 24 and adaptation 25_1 compressors connected with turbine 23 via shafts 26 and 27_1, respectively. Preliminary estimates and subsequent calculations have shown that frontal turbine 23, as the primary vapor turbine 16 of the synergetic engine, can be birotative owing to the powers of compressors 24 and 25_1 being as a rule of almost the same value.

The synergizer has two inlets: one of them is from a vehicle fuel tanks to pump 14 (In_1) and the other from primary vapor turbine 16 to non-controllable (two-position) valve 9 (In_2) and four outlets: from non-controllable valve 10 to primary hydrogen-gas heat exchanger 40 (Out_1), from controllable valve 2 to frontal combustion chamber 38 of the internal engine duct and terminal combustion chamber 45 of the external duct (Out_2 and Out_4, respectively) and from controllable valve 4 to a single high-pressure combustion chamber, the afterburning chamber 43 of the internal engine duct (Out_3).

First non-controllable valve 9 has one inlet and two outlets, second valve 10 has two inlets and one outlet, the exit from primary vapor turbine 16 being connected with the inlet to valve 9 and the outlet from valve 10 with the inlet to primary hydrogen-gas heat exchanger 40. Thus, in the fuel line of the engine a closed loop is formed containing some synergizer elements which ensure the existence of the loop and two primary external units of the fuel line where energy exchange between the hydrogen and incoming flow takes place. The hydrogen from the vehicle fuel tanks is passed to pump 14 then, as before, it is passed to the heated-medium inlet of heat exchanger 15, and from the additional outlet of pump 14 it is passed to controllable valve 3 where, together with part of the hydrogen flow which is also passed to valve 3 after having been put through some processes, it is passed farther to auxiliary turbine 18 which drives the pump, then it is passed through controllable valve 2 to low-pressure combustion chambers, the frontal chamber of internal duct 38 (Out_2) and terminal combustion chamber 45 (Out_4). An additional heat exchanger can be positioned between the additional outlet of pump 14 and valve 3 for cooling the structural elements of a vehicle and/or the power plant with cryogenic hydrogen.

The high-pressure hydrogen heated in heat exchanger 15 at first is passed to frontal vapor turbine 23 where it does a useful work and cools down then it is passed to one of the inlets to valve 10. Part of the hydrogen flow from primary vapor turbine 16 through one of the outlets from valve 9 is passed to the heating-medium inlet of heat exchanger-regenerator 15 where it is cooled down by the hydrogen from the fuel tanks and is compressed in recovery compressor 24, where the decrease of hydrogen pressure is compensated for its expansion in primary vapor turbine 16 and losses in the fuel line, then it is passed to the other inlet to valve 10. Further the united hydrogen flow from valve 10 is passed to primary hydrogen-gas heat exchanger 40 and primary vapor turbine 16, then part of it returns to valve 10.

The hydrogen flow from the other outlet of non-controllable valve 9 is split in valve 1, further its portion that is finally burned in the high-pressure combustion chamber is successively compressed in adaptation compressor 25_1 and, if conditions allow, in booster compressor 25_2 and through one of the outlets of controllable valve 4 it is passed to afterburning chamber 43 of the internal duct of the synergetic engine (outlet Out_3). The other portion of the hydrogen flow from valve 1 is passed, if conditions allow, through additional vapor turbine 23_3 driving booster compressor via shaft 27_2 and further it unites with the above-considered hydrogen flows at valves 5 and 3 or at their substitutes, ejectors 11 and 12, and is successively passed to the turbine of turbopump 18 and to low-pressure combustion chambers 38 and 45.

Such an arrangement of the synergizer leads to the fact that through its closed loop including the outlet Out_1, primary hydrogen-gas heat exchanger, primary vapor turbine and inlet In_2 is passed substantially greater hydrogen flow than that passed to the synergizer from the fuel tanks through the inlet In_1 and passed to the combustion chambers through the outlets Out_2, Out_3, and Out_4. Typically, the flow augmentation factor is close to 2, its exact

values being dependent on synergizer variant and flight regime, they will be given in subsequent report sections for various versions of the synergetic engine.

The first consequence of employment of the synergizer is the fact that the need for separating primary heat exchanger 40 into two series-parallel sections is eliminated, but in this case the hydrogen flow in it is no less than before. Furthermore, because now hydrogen flow passing through primary vapor turbine 16 also is approximately twice as much as before, to obtain the same or even greater power of turbine 16 its expansion ratio may be reduced by a factor of 3.5 - 4, that is, from 15 - 20 [1] to 4 - 5 and the pressure at the entry to turbine 16 may be correspondingly reduced and, with taking into consideration the two-fold flow increase, the maximum allowable pressure increases approximately to $p_t^* = 4$ MPa, the turbine open-flow area increases by an order of magnitude, and the blade height of its first stages is within technological limitations. The number of stages and length of the turbine as well as its mass which, as known, makes up a significant part of the mass of the entire engine (about 20 - 25 %) decrease by a factor of 1.5 - 2.

The pressure at the entry of frontal turbine 23 must be approximately 5 times greater than that at the entry to primary turbine 16, that is, about 20 MPa, but turbine 23 is not mechanically connected with the large-diameter compressors of the engine gas passage and, consequently, its diameter may be no more than 10 % of that of primary turbine 16. Because of this, with the relatively small open-flow area of turbine 23 the height of its blades is also within technological limitations. Its cross-sectional area will make up about 1 % and the cross-sectional areas of hydrogen compressors 24 and 25_1 connected via the shafts with frontal turbine 23 will also be no more than 5 % of the corresponding quantity of primary vapor turbine 16. This being so, the total mass of these units will be, as estimates have shown, substantially less than the mass reduction of turbine 16 due to decreasing its length and the total mass of the engine structure decreases owing to synergizer employment.

Recovery compressor 24 compresses the hydrogen flow cooled in heat exchanger-regenerator 15 and allows restoring the pressure in the closed loop of the synergizer to the previous level after having it dropped at primary vapor turbine 16. Its pressure ratio is several percent greater than the expansion ratio of turbine 16. Adaptation compressor 25_1 allows reducing the pressure at the outlet from pump 14 and, as a consequence, the pressure throughout the fuel line, according to the value of its pressure ratio which is approximately equal to $\pi_c = 1.8 - 1.9$. It is this unit that allows being ultimately within the blade height limitations of primary vapor turbine 16 at an engine thrust of about 300 kN. In addition, the described combination of the adaptation compressor, frontal turbine and valves makes it possible to remove part of enthalpy from the closed loop of the synergizer, reduce the hydrogen temperature at the outlet Out_1 and improve operating conditions for terminal 41 and booster 47 compressors of the gas passage of the synergetic engine, which results in enhancing its thrust and economic characteristic.

The combination of the controllable valves 4 and 5 (or valve 5 and ejector 11) provides the constancy of the operating modes of all bladed units of the synergizer, except for the turbopump, despite the variation of the hydrogen flow rate in the engine combustion chambers during the flight of the vehicle along the acceleration trajectory. At the maximum hydrogen flow rate in afterburning chamber 43, which takes place at the maximum flight Mach number, all hydrogen entering the valve 4 is by-passed to combustion chamber 43. At lower Mach number, the share of the hydrogen flow, which goes through adaptation compressor 25_1, is the same, but because the fuel consumption in combustion chamber 43 is lower, part of hydrogen from the valve 4 is by-passed into valve 5 or ejector 11 substituting this valve. The further way of the hydrogen evidently require no verbal explanations (see Fig. 1).

Booster hydrogen compressor 25_2 and additional vapor turbine 23_3 allow a further decrease in the maximum pressure in the fuel line of the synergetic engine due to a more thorough matching pressures of gas and hydrogen in the combustion chambers of low and high pressures. Sizes and masses of these units, as well as units of the synergizer, are not large. However, as computations show, the maximum achievable pressure ratio of booster compressor 25_2 for the considered versions of the synergetic engine with the above described synergizer, is very low (no more than $\pi_c = 1.1$), and therefore, the expediency of the use of this pair of bladed units should be considered during a more detailed investigation of characteristics of a concrete version of the engine with the synergizer of such a type.

A version of the hypersonic synergetic air-breathing jet engine named SJ-3, differing from the SJ-2 version [1] in using the aforedescribed variant of the synergizer, has been studied in the framework of the second-level computational model with allowance for the real gas properties (see [1]). Presented for comparison are also main thrust and economic performance of the TE-25 version of the turbo-expander power plant for which operating modes of the frontal compressor lie within the allowable envelope of characteristics of a typical compressor with controllable guide blades [1]. Values of efficiency coefficients for individual units and restrictions on main parameters of the engine versions considered below coincide with values used earlier and are described in detail in the previous report [1]. It is assumed that efficiency values of all vapor turbines in the synergizer are the same as that of the primary vapor turbine and are equal to $\eta_t = 0.85$, and for hydrogen compressors $\eta_c = 0.80$.

The results of computations of all versions and variants of engines are presented in Tables 1 - 6. Table 1 gives main parameters of the engines under study. Here, the following nomenclature is used: $\pi_{fc}{}^{o}$ - pressure ratio of frontal compressor 37 at M = 0; π_{pt} - expansion ratio of primary vapor turbine 16; $T_{pt}{}^{o}$ - temperature of hydrogen at the entry to turbine 16 at M = 0; π_{ft} - expansion ratio of frontal vapor turbine 23; π_{gt} - expansion ratio of gas turbine 39; k_t - coefficient of "temperature handling", i.e., the ratio of the hydrogen temperature at the entry to the primary vapor turbine at the maximum flight Mach number (M_{max} = 5.5) to $T_{pt}{}^{o}$; $\beta_s{}^{o}$ - flow rate coefficient of the synergizer, i.e., the share of the hydrogen flow from the main outlet of pump 14, effectively used in the synergizer, referenced to the total hydrogen flow at the inlet to the pump at M = 0; m_2 - hydrogen by-pass ratio, i.e., the ratio of the hydrogen flow through recovery compressor 24 to the hydrogen flow through frontal turbine 23 (in this case the coefficient of increasing hydrogen flow for primary hydrogen-gas heat exchanger 40 and primary vapor turbine 16 due to the operation of the synergizer is equal to m_2 + 1).

Basic characteristics of the engines considered are shown in Tables 2 - 5 at the start Mach number M = 0; at the transonic M = 1.2, which approximately corresponds to the so-called "transonic neck" with a minimum ratio of the engine thrust to the drag of a hypersonic vehicle; at an intermediate supersonic Mach number M = 3, whose neighborhood is a sort of the transition zone between low and high speeds, and at the maximum considered Mach number M = 5.5. In this case, as in the previous reports, R - specific thrust of the engine; I_{sp} - specific impulse, $q(\lambda)$ - dimensionless gas-dynamic flow rate function, P/S - thrust loading, c_p - thrust coefficient, p_{max} - maximum pressure in the fuel line, π_I - pressure ratio of the gas passing from the entry of the frontal compressor to the entry of the nozzle of the internal duct of the gas-flow passage, π_{II} - analogous property for the external duct, m_1 - air by-pass ratio of the synergetic engine, β_s - aforementioned flow rate coefficient of the synergizer.

In Table 6, $q_3(\lambda)$ and $q_5(\lambda)$ - are the dimensionless gas-dynamic functions of flow rate through the engine at M = 1.2 and M = M_{max} = 5.5, respectively, $k_q = q_3/q_5$ is the ratio of the previous properties, k_q^* is the previous ratio related to its value for the TE-25 turbo-expander engine.

Three variants of the SJ-3 version of the synergetic air-breathing engine are considered in this report. The choice of basic parameters (see Table 1) is made on the basis of computations for the SJ-2 version [1], however, it was taken into consideration that for matching the characteristics of the frontal compressor and all the other units of the engine it is advisable to increase the pressure ratio of the frontal compressor, $\pi_{fc}{}^{o}$. The hydrogen temperature at the entry to the primary vapor turbine $T_{pt}{}^{o}$ for all variants of the synergetic engine considered below is selected as the least allowable value from the standpoint of the birotativity conditions (see [1]). The only exception is the variant SJ-3-1, where this temperature can be lowered to approximately 1000 K. Preliminary assessments have shown that at the expansion ratio of the frontal vapor turbine π_{ft} = 5 - 5.5 both the vapor turbines simultaneously reach their blade-height limits. Obviously, this value of the indicated parameter is the optimum one.

At M = 0, the specific impulse and thrust loading of the SJ-3 version of the synergetic engine exceed the corresponding characteristics of the turbo-expander engine TE-25 by a factor of 1.33 - 1.39 (see Table 2). In this case its air by-pass ratio m_1 is about 0.7, whereas the pressure ratio in the internal duct almost reaches 22. Maximum pressures in the fuel line of the engines reach 25 - 28 MPa which somewhat exceed the maximum allowable pressures at the thrust P^{o} = 300 kN, the diameter ratio of the primary vapor turbine and the frontal compressor d_{pt}/d_{fc} = 0.6, and the subcriticality degree at the entry to the primary vapor turbine corresponds to the value $q(\lambda)_{pt}$ = 0.4. However, according to experts at Central Institute of Aviation Motors (CIAM), minimum value of $q(\lambda)_{pt}$ can be equal to 0.3, which allows meeting the on blade-height limitations at these pressures. Besides, the expansion ratio of the primary vapor turbine can be decreased to π_{pt} = 4.5 - 4.0, in this case maximum pressures in the fuel system will decrease by a factor of 1.15 - 1.3 and be close to 20 MPa.

At the maximum design Mach number M_{max} = 5.5, the specific impulse of the SJ-3 engine is greater than that of the turbo-expander engine by a factor of 1.10 and the thrust loading by a factor of 1.56 - 1.89 (see Table 5), however this version of the synergetic power plant cannot be implemented in practice as well, taking into consideration of today characteristics of bladed units. The parameter $q_5(\lambda)$, characterizing the air flow both through the frontal compressor and the engine as a whole at the maximum Mach number for the turbo-expander engine TE-25, lies on the bottom boundary of the operating envelope and its value is 0.465 (see Table 6). Analogous parameters of the SJ-3 engine variants, determined from the condition for the constancy of modes of all bladed units, excluding the frontal compressor and turbopump, are greater by a factor of 1.43 - 1.72, which exceeds allowable limits for the frontal compressor (see Fig. 4 in [1]). Thus, it is necessary to find means to match flow characteristics of the frontal compressor and the other bladed units of the synergetic engine at high flight speeds. The following section of this report is dedicated to this topic.

3. Solution of the second technological problem of creating the synergetic engine: version SJ-4

The mismatch of the flow characteristics of the frontal compressor and the inverse-cycle module of the synergetic engine decreases as the pressure ratio π_{fc}^{o} of the compressor increases, according to an analysis of the SJ-3 parameters. Besides, since temperatures at the entry to the primary vapor turbine are significantly lower than maximum allowable ones ($(T_{pt})_{max}$ = 1500 K), "temperature handling" can be applied to this turbine, which is equivalent to decreasing the maximum flight Mach number. In combination with the air by-pass around the frontal compressor, realizable without increasing the cross-sectional area of the engine at the entry to the compressor [3,5], it is possible to completely solve the second fundamental technological problem associated with the creation of the synergetic engine.

Indeed, (see Fig. 2), duct 50 can be formed around frontal compressor 37 to by-pass air to the engine gas-flow passage with controllable doors 51 and 52 at the inlet to duct 50 and at the outlet from this duct, respectively. Through doors 52 part of the airflow from frontal compressor 37 is passed to the external passage where air mixes with the flow from duct 50. For the air by-pass duct not to increase the cross-section area of the engine and to simplify the structure of the controllable doors, the cross section of the external boundaries of duct 50 and the entire external duct of the engine gas-flow passage can be made square. In this case, duct 50 consists of four channels placed into the space between the external square boundaries and the turbo-compressor module circular in its cross section, i.e., in the space where a square-to-round adapter is usually located. Doors 51 in their closed position do perform the role of such an adapter.

In the limiting case, the coefficient of increasing the open flow area $k_b = 4/\pi \approx 1.273$; in a more realistic case, when the cross section of the internal boundary of the by-pass duct at its entry is a regular octahedron, k_b = 1.207. Therefore, one can reckon on almost 20 % increase of the air flow through the engine at $M = M_{max}$. According to assessments, any combination of two from the three considered means: increasing the frontal compressor pressure ratio, "temperature handling", and air by-pass allows one to solve the second fundamental technological problem of the synergetic engine at the expense of a somewhat decreased thrust level at high hypersonic flight speeds.

However, preliminary consideration of the integration problems of the synergetic air-breathing jet engine with a typical air intake of hypersonic aircraft has shown that using such ways to solve the problem of matching the characteristics of the frontal compressor and the inverse-cycle module the synergetic engine is not able to provide acceleration of the aircraft along the entire flight trajectory. This relates to the fact that even the turbo-expander engine TE-25 with its air pumping characteristics provides in the "transonic neck" at M = 1 - 1.5 only a minimally needed exceeding of thrust over drag for a typical vehicle designed for the maximum Mach number M = 12 - 15. In this case the ratio of dimensionless functions of air flows at transonic speeds and at the maximum Mach number M = 5.5 (the design value for the air intake) is about $q_3/q_5 \approx 0.53$ (see Table 6), which results in high drag due to air spillage on the intake lips at transonic Mach numbers (Fig. 3, line 2). For synergetic engine of the aforedescribed type, the ratio q_3/q_5 will be 40 - 50 % greater, the drag of the intake lips will be higher, and the total drag of the aircraft with the operating power plant can exceed the engine thrust at transonic speeds.

Because of this, it was decided to provide matching the characteristics the frontal compressor and the inverse-cycle module of the synergetic engine at moderate pressure ratios of the frontal compressor ($\pi_c^{o} \approx 4$) without air by-pass, and to use the aforedescribed procedure, as may be required, for the integration of the engine and the air intake of the hypersonic aircraft.

For matching the characteristics of the frontal compressor and the inverse-cycle module, the SJ-4 synergetic engine uses, in parallel with "temperature handling", the so-called "mass-flow handling", which consists in the following: at low flight speeds the synergizer uses not the entire hydrogen flow delivered to the pump, but only a part of the flow, which is characterized by the flow coefficient of the synergizer, β_s (see Tables 1 and 2). The flow coefficient reaches it maximum value β_s = 1 only at the maximum Mach number $M = M_{max}$ (see Table 5). In this case, to compensate the decrease in hydrogen flow through the primary hydrogen-gas heat exchanger, the air by-pass ratio m_1 of the synergetic engine is increased at low flight speeds.

As to the influence on the characteristics of the frontal compressor, "mass-flow handling" is equivalent to "temperature handling". Besides, "mass-flow handling" allows one to significantly decrease the air by-pass ratio m_1 of the synergetic engine at maximum (design value for the intake) Mach number (see Tables 2 - 5) and additionally decrease the ratio q_3/q_5 (see Table 6), thus enhancing matching the engine and the air intake and providing an excess of thrust over drag at transonic flight speeds.

All computations for the SJ-4 version were performed at the stoichiometric fuel consumption (β = 1). "Temperature handling" was used from the start to transonic and low supersonic speeds so that the ratio between the total temperature of hydrogen at the entry to the primary vapor turbine T_{pt} and the total temperature of air at the entry to the engine T_1 remained, while it was possible, constant (T_{pt}/T_1 = const). In this case the air by-pass ratio m_1 was fixed, whereas the flow coefficient of the synergizer β_s somewhat increased due to the need for

balancing heat fluxes in the primary hydrogen-gas heat exchanger with the changed chemical composition of the gas. Then, linearly with the temperature at the entry to the engine, the "mass-flow handling" is performed. It should be noted that in all design cases, despite the significant deviations of thermodynamic characteristics of the real gases from the characteristics of a perfect gas (for example, specific heat capacity of the combustion products at constant pressure in the frontal combustion chamber increases almost by a factor of 1.6 compared to the specific heat capacity at the entry to the frontal compressor, not by 15 % as in the first-level computational model), the deviations from the nominal regime of all bladed units of the synergizer and inverse-cycle module, except for the booster compressor, lie within a range of ± 0.5 %. The booster compressor has the maximum range of deviations from the nominal mode which is somewhat less than ± 1.5 % at maximum coefficients of "temperature handling". For the final variant SJ-4-6 these deviations lie within limits ± 1 %.

In the framework of the second-level model, extensive computations to study the SJ-4 version of the hypersonic synergetic air-breathing engine were performed, their main results being presented in Tables 1 - 6. The expansion ratio of the primary vapor turbine π_{pt}, the expansion ratio of the frontal vapor turbine π_{ft}, and the hydrogen by-pass ratio of the synergetic engine m_2 were fixed at values close to optimum ones taking into account of today restrictions on an engine of the type considered. The temperature of hydrogen at the entry to the primary vapor turbine at M = 0, T_{pt}°, was chosen as a minimum value with allowance for the birotativity restriction [1]. The pressure ratio of the frontal compressor at M = 0, π_{fc}°, the coefficient of "temperature handling", k_t, and the flow coefficient of the synergizer β_s° were changed in concord in search for their optimum combination. In addition, the best expansion ratio of the gas turbine, π_{gt}, was determined with allowance for structural considerations.

The ranges of parameters variations (π_{fc}° = 3.5 - 4.5, k_t = 1.0 - 1.27, β_s° = 0.8 - 1.0) are defined by restrictions specified earlier [1]. The temperature of hydrogen from the intermediate outlet of the pump after passage through the auxiliary heat exchanger was taken equal to 500 K. Increase in the pressure ratio of the frontal compressor, π_c°, and decrease in the flow coefficient of the synergizer, β_s°, lead to decreasing the dimensionless flow function at M = M_{max}, which means the possibility of matching the pumping characteristics of the frontal compressor and inverse-cycle module of the synergetic engine, decrease in β_s° leading to degradation of the thrust and economic characteristics at low Mach numbers (compare variants SJ-3-1, SJ-4-1 and SJ-4-2). Thus, the optimum flow coefficient of synergizer must be greatest possible from all restrictions and its value, according to performed computations, must be approximately equal to $(\beta_s^{\circ})_{opt} \approx 0.9$. An excessive increase in the pressure ratio of the frontal compressor leads to impossibility of using "temperature handling" and an excessive decrease in the thrust level at high supersonic speeds (compare variants SJ-4-3, SJ-4-5 and SJ-4-8). Because of this, for the SJ-4 version $(\pi_c^{\circ})_{opt} \approx 4$. While decreasing the expansion ratio of the gas turbine, π_{gt}, from 2.5 to 1.875 leads to a degradation of the thrust and economic characteristics at M = 0 by about 1 %, it allows increasing thrust at high supersonic speeds by about 3 % and decreases the maximum pressure in the fuel system by about 17 % (compare variants SJ-4-4, SJ-4-5, SJ-4-6). Besides, the powers of the gas turbine and terminal compressor decrease by a factor 1.4, which leads to a corresponding decrease in their structural masses as well as to an increase in gas pressure in the primary hydrogen-gas heat exchanger and a decrease in its mass by about 25 % due to this factor. The value $\pi_{gt} \approx 1.875$ provides the simultaneous reaching of limits on the maximum allowable temperatures both for the primary vapor turbine (T_{max} = 1500 K) and the gas turbine (T_{max} = 2000 K), therefore, this value is the optimum one. The coefficient of "temperature handling" must be a maximum, and at the indicated conditions $(k_t)_{opt} \approx 1.175$. Thus, for the considered version SJ-4 of the synergetic engine, the variant SJ-4-6 as a whole has the best characteristics.

The performance curve of the frontal compressor of this variant lies within the operating envelope of a typical compressor with controllable guiding devices, however the ratio q_3/q_5 is about 30 % greater than that of the turbo-expander engine TE-25 ($k_q^* \approx 1.3$, see Table 6), which points to great difficulties in the integration of the chosen variant of the SJ-4 synergetic engine version and a typical air intake of a hypersonic aircraft.

4. Characteristics optimization of the synergetic engine: version SJ-5

For further enhancing the performance of the hypersonic synergetic air-breathing jet engine, it is necessary to increase its hydrogen by-pass ratio and provide values $m_2 > 1$. In this case, the temperature of hydrogen at the heating-medium outlet of heat exchanger-regenerator 15 (see Fig. 1) quickly rises, the flow through recovery compressor 24 increases too and especially its power; the available power for adaptation compressor 25_1 decreases and frontal turbine 23 first loses its capability of being birotative and then the use of adaptation compressor 25_1 becomes pointless at all and part of its functions devolves on booster compressor 25_2.

However, in this case, the expansion ratio of frontal turbine 23 turns out to be, as a rule, less than the optimum value π_{ft} = 5 - 5.5, which degrades the characteristics of the synergetic engine. Because of this, it is advisable that

the frontal turbine drive one more unit not requiring too great power. Obviously, such a unit can be a pump, but in the above versions of the engine, the turbopump, unlike all bladed units of the synergizer and inverse-cycle module, does not retain its operating mode unchanged along the entire acceleration trajectory of a hypersonic vehicle and its mere addition to the frontal turbine would destroy the whole concept of the synergetic engine.

If we adjust the turbopump for the maximum fuel flow and at other operating modes the flow excess is by-passed to the inlet of the pump or delivered to fuel tanks of the aircraft, it will be possible to provide the constancy of the operating mode of the pump, which allows one to create a third variant of the synergizer shown in Fig. 4.

Pump 14 is driven by frontal turbine 23 via shaft 19, and auxiliary vapor turbine 18 becomes unnecessary. For matching hydrogen pressures at the outlet of pump 14, at the inlet to heat exchanger-regenerator 15, and at the inlet to pump 14, in lines connecting these units an additional control valve 67 and throttle valves 68 and 69 must be placed. Valve 67 has two inlets and one outlet, and each of the throttle valves has one inlet and two outlets, the first inlet of valve 67 being connected with the fuel tanks of a vehicle, the second inlet of valve 67 being connected to the first outlet of throttle valve 69, and the outlet of controllable valve 67 being connected to the inlet of pump 14. The outlet from pump 14 is in turn connected to the inlet of throttle valve 68, whose first outlet is connected to the heated-medium inlet to heat exchanger-regenerator 15, its second outlet is connected with the inlet to throttle valve 69, whose second outlet is connected with the first inlet of control valve 3 or ejector 12 replacing it.

It is also advisable to place in the fuel line in front of additional vapor turbine 23_3, which drives booster compressor 25_2, auxiliary heat exchanger 70 for cooling the most heated components of the engine, for example, the neighborhood of the throat of the external duct nozzle 46. In this case, the enthalpy at the entry to turbine 23_3 will rise, which will allow one to increase the pressure ratio of the booster compressor 25_2 and decrease thereby the maximum pressure in the fuel system.

To eliminate cavitation in primary fuel pump 14, ejector 13 can be placed as a booster pump in the line between hydrogen tanks and control valve 67. In this case ejector 13 has two inlets and one outlet, the primary-gas inlet of the ejector is connected to the intermediate outlet of primary pump 14, the entrained-gas inlet of the ejector is connected with fuel tanks, and the outlet of the ejector is connected with the inlet of control valve 67. One of the outlets of control valve 4 and the outlet of the additional turbine 23_3, can be, as before, connected with control valve 5 or ejector 11 substituting it.

Overall, the third variant of the synergizer, shown in Fig. 4, can be simpler and somewhat more efficient than the previous variant. The version of the synergetic engine with this synergizer was designated as SJ-5.

Computations of the characteristics of this version of the engine were performed at a hydrogen by-pass ratio of m_2 = 1.1 - 1.125. In this case, hydrogen flow in the closed loop of the synergizer exceeds the flow at the primary outlet of the pump by a factor of 2.1 - 2.125, and an opportunity occurs to increase the expansion ratio of the primary turbine by 5 % to $\pi_{pt} = 5.25$ at the same, as before, limits on the height of its blades. The expansion ratio of the frontal turbine must be correspondingly decreased, i.e., $\pi_{ft} \leq 5.25$ (in this version of the synergetic engine this property is computed, not specified). The flow coefficient of the synergizer at M = 0 is equal to $\beta_s^\circ = 0.9$ for all considered versions SJ-5.

The SJ-5-1 variant has no additional heat exchanger 70 and represents, with allowance for structural changes, an analog of the SJ-4-5 of the previous version. Generally, the SJ-5-1 engine has no obvious advantages over the SJ-4-5: the former has 4 - 5 % greater thrust levels at high supersonic speeds, but the latter has the 10 - 25 % lesser maximum pressure in the fuel system over the entire acceleration trajectory. But of most importance is the fact that the initial temperature at the entry to the primary vapor turbine T_{pt}° in the new version is decreased by 8 % (by about 100 K, see Table 1), which allows one to increase the temperature handling coefficient k_t and consider the use of variants with higher pressure ratios at the frontal compressor, $\pi_{fc}^\circ > 4$.

The version SJ-5-2 differs from the version SJ-5-1 in that its synergizer is supplemented by auxiliary heat exchanger 70 which heats hydrogen up to 1000 K at M = 0 and the heating proceeds in accordance with temperature growth at the entry to primary vapor turbine T_{pt} during its handling . In addition, the "temperature handling" with the aim to increase air flow through the engine at transonic speeds is performed more intensively, in such a manner that an increase in hydrogen temperature at the entry to the primary vapor turbine is in excess of the temperature growth at the entry to the frontal compressor to the point of completing this process (as before, the "temperature handling" is completed with the same temperature at M = 1.84).

The employment of auxiliary heat exchanger has led to decreasing maximum pressures p_{max} in the fuel system by 5 - 10 % and the more intensive "temperature handling" allows a 2 % increase in the air flow and thrust of the engine SJ-5-2 within the "transonic neck". Transition to the near-optimum value of the expansion ratio of the gas turbine $\pi_{gt} = 1.875$ (variant SJ-5-3) has resulted in further decreasing the values of p_{max} and to somewhat (by 1 %) increasing thrust at high supersonic speeds.

Clearly an increase in the pressure ratio of the frontal compressor π_{fc}° (variants SJ-5-4 and SJ-5-5) leads to improving thrust and economic characteristics of the synergetic engine at low and, to some extent, at transonic

flying speeds and to decreasing thrust level beginning with the supersonic portion of the acceleration trajectory. It should be noted that the version SJ-5 allows significant "temperature handling" (k_t = 1.15) even with π_{fc}° = 4.5 and existing limitations. The greater is the pressure ratio of the frontal compressor, the easier is the integration of the synergetic engine with a standard air intake of a hypersonic vehicle (see values of the parameter k_q in Table 6). But taken as an object for further studies was the variant SJ-5-4 having π_{fc}° = 4.25 and the higher thrust level at the second portion of the acceleration trajectory than that of the variant SJ-5-5.

The control law for the variant SJ-5-6 of the synergetic engine on the portion of the trajectory after completing the temperature handling (at M = 1.75) differs from that for the variant SJ-5-4 in that the rate of increasing the flow coefficient β_s of the synergizer with total temperature at the engine inlet is raised by a factor of 5 and this process is completed at M = 2.865 but not at M = 5.5, as before. The air by-pass ratio m_1 continues to be fixed on this portion of the trajectory, and following the balance condition for the heat fluxes in the primary hydrogen-gas heat exchanger the fuel consumption becomes less than the stoichiometric one. Further the parameter β increases linearly with temperature at the engine up to 1 at M = M_{max} = 5.5. Thus, air flow rate and engine thrust at supersonic speeds increase. For example, at M = 3 the relative fuel consumption is β = 0.928 and the specific thrust R decreases by 4 % but both the specific impulse I_{sp} and the thrust loading P/S (or the thrust coefficient c_p) increase by about 3 % (see Table 4). Thus, when employing the synergizer, its transition to the maximum mode with β_s = 1 can improve the thrust and economic characteristics of the acceleration engine even if it is accompanied by deviations from the stoichiometric mode of operation of the combustion chambers.

The variant SJ-5-7 differs from the preceding one in the reduction of the aerothermodynamic characteristics of the primary hydrogen-gas heat exchanger. Its efficiency is decreased from η_{pe} = 0.800 down to η_{pe} = 0.775, total pressure coefficient is decreased from ν_{pe} = 0.95 down to ν_{pe} = 0.90, and minimum temperature differential at the cold end of the heat exchanger is increased from ΔT_{max} = 100 K up to ΔT_{max} = 120 K. In so doing, according to estimates, the structural mass of the heat exchanger is to be decreased by 10 - 12 %. In this case the degradation of the basic thrust and economic characteristics of the synergetic engine makes up from 1 % at low speeds to 0.5 % at high speeds. Maximum pressures in the fuel system therewith are decreased by 14 %.

The control law for the variant SJ-5-8 of the synergetic engine on the portion of the trajectory after completing the increase of the flow coefficient β_s of the synergizer up to 1 (at M = 2.865) differs from that for the variant SJ-5-7 in that over the half (judging from temperature) the remainder of the trajectory up to M = 4.36 the relative fuel consumption is fixed to be β = 0.927, and further this parameter increases linearly with temperature up to 1 at M = M_{max} = 5.5, that is, twice as faster as before. This results in the further minor increase of air flow at supersonic speeds and corresponding improvement of the thrust and economic indices of the synergetic engine. Although in this case these effects are very small and have practically no reflection in the data presented in Table 4 (in Tables 2, 3 and 5 the distinctions between the veariants SJ-5-7 and SJ-5-8 are not to be), one should conclude that any alternative ways to increase air flow through the synergetic engine at trans- and supersonic speeds can not only favor more effective integration of the engine and air intake but therewith improve, as aerodynamicists would say, the characteristics of a "isolated engine".

The ratio of the air flows through the variants S-5-7 and SJ-5-8 of the synergetic engine at transonic speeds and at the maximum design flying speed are $q_3/q_5 \approx 0.65$, which is 20 % greater than that of the turbo-expander engine TE-25 (see Table 6). This implies that within the "transonic neck" the spillage drag of the considered versions of the synergetic engine will be greater than that of the turbo-expander power plant and at low thrust-to-weight ratios of a hypersonic vehicle the fuel consumption in acceleration will be less for the engine TE-25 and at high thrust-to-weight ratios less for the engines SJ-5-7 and SJ-5-8.

The maximum pressure at the entry to the frontal turbines of the engines SJ-5-7 and SJ-5-8 at M = 0 makes up 20.3 MPa and the pressure at the entry to the vapor turbine is 4.15 MPa, which allows satisfying the blade-height limitations at the entries to these turbines at the blade-tip speed of the frontal compressor u = 700 m/s and the diameter ratio of the primary vapor turbine and compressor d_{pt}/d_{fc} = 0.60 [2] at the subcriticality degree expressed by the value of the dimensionless flow rate function $q(\lambda) \approx 0.40$ for the frontal vapor turbine and $q(\lambda) \approx 0.35$ for the primary one. The variant SJ-5-9 of the synergetic engine meets the blade-height limitation condition $h \geq 10$ mm for both the vapor turbines at $q(\lambda)$ = 0.40, the decrease of specific impulse therewith being about 1 % as compared to the engines SJ-5-7 and SJ-5-8 at M = 0 and about 0.2 % at M = 5.5; these losses are mainly associated with decreasing the pressure ratio of the frontal compressor (see Tables 1 - 6). It should be noted that to simultaneously reach the blade-height limitations for both the vapor turbine, one had increase hydrogen by-pass ratio of the synergizer up to m_2 = 1.125 and to decrease the expansion ratio of the gas turbine down to π_{gt} = 1.85. From this it follows that it is rather difficult to fully optimize the synergetic engine and simultaneously reach all the limitations. So these limitations must previously be clearly brought to agreement with all parties interested in designing an optimum hypersonic synergetic engine.

Fig. 5 shows the relationships $\pi_{fc} = f(q(\lambda))$ (curves 1 and 2, respectively) for the synergetic engine SJ-5-8 and turbo-expander engine TE-25 and the approximate boundaries of the operating zone of the compressor of the engine SJ-5-8 ($\pi_c^\circ = 4.25$). In addition, the relationship $\pi_{fc} = f(q(\lambda))$ is shown for the internal duct of the synergetic engine (curve 3). It is evident that line 3 goes outside the operating zone deviating rightward. Such a behavior of the dimensionless flow rate function ensures stability of operation of the inverse-cycle module of this engine. But due to decreasing the air by-pass ratio m_1 with flying Mach number, curve 1 for the frontal compressor of the synergetic engine remains within the limits of its operating zone. As a result of the greater start pressure ratio π_c° and "temperature and mass-flow handling", curve 1 is in the region of higher values of pressure ratios and flow rates than curve 2 for the turbo-expander engine, which improves the characteristics of the engine SJ-5-8. Points in curve 1 show the instants at which the changes of sign of the control law of the synergetic engine occur.

Fig. 6 shows the variations of the specific impulse I_{sp} and thrust coefficient c_p (thrust loading at M = 0) for the variants SJ-5-7 and SJ-5-8 of the synergetic engine and the turbo-expander engine TE-25. The specific impulse of the synergetic engines are 1.3 - 1.1 times greater, on the average the gain amounts to about 18 %. Engine inlet areas being equal, thrust loading is 1.25 - 1.35 times greater, on the average the gain is close to 30 %. With the same start thrust, the average thrust of the synergetic engines are practically equal to that of the turbo-expander power plant, the cross-section area of the synergetic engine makes up 76 % of that of the TE-25. The fuel required for acceleration with synergetic engines is about 75 % of the fuel required by the turbo-expander engine, at equal areas at the entry to the frontal compressor, and about 85 % at equal start thrusts, if the thrust-to-drag ratio average over the trajectory for the turbo-expander engine is P/D = 2.

5. Preliminary study of the problem on integrating the synergetic engine and air intake of a hypersonic vehicle

Up to this point the performance of air-breathing engines were considered as explicitly independent of the air intakes of a vehicle and the problems of their integration were implicitly accounted for only through the air-flow matching coefficient k_q which represents the ratio of dimensionless air flows at maximum design engine operating speed and in the "transonic neck" (see Table 6). Early in the conceptual design phase of an all-new power plant it was justified, but to perform the final refinement of the layout of the hypersonic synergetic air-breathing engine one should consider in more detail the problems of its integration with the air intake and, if necessary, introduce modifications to the layout being proposed.

Taken as a proof-of-concept aircraft which uses the synergetic engine for acceleration up to Mach number M = 5.5 was a standard hypersonic vehicle with a maximum flying Mach number of $M_c = 15$ of the air-breathing regime. Although the preliminary optimization of technical and economic parameters of reusable aerospace launchers does not suggest that the Mach number be more than M_c = 12 - 12.5 [6], to study the integration problems of the synergetic engine the vehicle variant was chosen that imposes somewhat excessive requirements for the air-flow characteristics of an acceleration engine.

The level of start thrust-to-weight ratio typical of such vehicles is $P_{sp}^\circ = P^\circ/(m^\circ g) \approx 0.6$ where P° is the start thrust, m° is the start mass, g is the gravitational acceleration, so the values of start thrust-to-weight ratios were considered ranging within P_{sp}° = 0.55 - 0.65. Fig. 7 shows the variations of the relative fuel burn $f = \Delta m_f/m^\circ$ (Δm_f is the fuel burn for accelerating the above indicated vehicle from M = 0 to M = 5.5) as a function of the parameter P_{sp}° for combined power plants consisting of the turbo-compressor and scramjet air-breathing engines positioned in parallel ducts (calculations were performed by V.Buzuluk, TsAGI). Inlet area of the air intake was defined by the scramjet characteristics and was adopted equal for both the power plants, in so doing for the synergetic engine it turned out to be somewhat oversized. The ratio of the scramjet throat area to the inlet area of the air intake was 0.15. The scramjet duct is to open at M = 0 and its rate-of-flow capacity was controlled in an optimum manner with taking into account the limits for deflection angles of the entry wedges of the external-compression intake. The scramjet was assumed to be lighted up at M = 5.5.

Curve 1 corresponds to the characteristics of the synergetic engine SJ-5-7, curve 2 corresponds to those of the turbo-expander engine TE-25. At thrust-to-weight ratios of $P_{sp}^\circ < 0.56$ fuel burn for acceleration is lesser when using the turbo-expander engine, but at $P_{sp}^\circ \geq 0.56$ the pattern is reversed. It is associated with the fact that the average specific impulse of the synergetic engine SJ-5-7 on the acceleration trajectory is 1.18 times more than that of the turbo-expander engine TE-25. Their average thrusts without regard for losses at equal start thrusts are practically the same, within the "transonic neck" the thrust of the SJ-5-7 under this condition is 1 - 2 % greater than that of the TE-25 (see Tables 2 - 5). But due to the coefficient k_q being 20 % greater (see Table 6), in transonic regimes the lesser air portion is passed through the synergetic engine duct and its spillage drag is some greater (see Fig. 3, where line 1 shows the variation of the spillage drag coefficient C_D^b with the flying Mach

number M for the synergetic engine and curve 2 for the turbo-expander engine, with intake area being taken as a characteristic area). With the engine thrust being only slightly greater than the total drag of the hypersonic vehicle within the "transonic neck" where in the cases being considered the effective specific impulse I_{ef} decreases practically by an order of magnitude as compared to nominal I_{sp} values, even a comparatively small increase in drag becomes very substantial. At the thrust-to-weight ratio $P_{sp}^{o} = 0.6$ the minimum value of the effective specific impulse on the trajectory at M = 1.25 amounts to $I_{ef} = 0.42 \cdot 10^4$ m/s for the synergetic engine at the nominal specific impulse $I_{sp} = 5.27 \cdot 10^4$ m/s and $I_{ef} = 0.46 \cdot 10^4$ m/s for the turbo-expander engine at $I_{sp} = 4.29 \cdot 10^4$ m/s. It should be noted that despite the comparatively small combustion efficiency in the scramjet duct at transonic speeds this procedure may still turn out to be useful in this regime for increasing the thrust of the combined power plant and, consequently, for reducing the total fuel burn for acceleration up to M = 5.5.

With the thrust-to-weight ratio $P_{sp}^{o} = 0.6$ the relative fuel burn for acceleration up to the beginning of the scramjet operation is f = 11.1 % for the synergetic variant SJ-5-7 and 12.0 % for the turbo-expander engine TE-25. With $P_{sp}^{o} = 0.65$ these quantities are 9.8 % and 10.9 %, respectively. For a more realistic hypersonic vehicle with the maximum flying Mach number in the air-breathing regime $M_c = 12 - 12.5$ whose base area and, correspondingly, base drag at transonic speeds will be lesser the fuel burn for acceleration when using both the engines will decrease and the advantage of the synergetic engine increase. Thus, the lower bound of the gain in fuel burn for the engine SJ-5-7 as compared to the turbo-expander engine is 10 % or 1.1 % of the start mass of the vehicle.

But the work on the integration of the intake and synergetic power plant is only in its early stage. If the air flow through the synergetic engine in the "transonic neck" is increased by 20 %, its fuel consumption characteristics will be obtained practically equal to those of the turbo-expander engine TE-25. Under this condition the estimates made in the end of the preceding section of the report will be valid here and the gain in fuel burn at the same start thrust will be 15 % or about 1.7 % of the start mass of the vehicle. For this to be done, it is necessary to make air by-pass around the frontal compressor which confines air flow at transonic speeds thus using the idea described in the beginning of the third section of the report. In addition, according to computed results for the versions SJ-5-6 ÷ SJ-5-8 of the synergetic engine it is advisable not to limit oneself to the neighborhood of the "transonic neck" but to use air by-pass throughout the flying Mach number range when it is possible according to limitations of the engine parameters. As a consequence, the thrust loading and specific impulse of the synergetic engine of a new version (its first variant SJ-6-1 is equivalent to that of SJ-5-8 with the exception of the air by-pass), will increase thus leading to the additional reduction of the fuel burn and the plots $f(P_{sp}^{o})$ for the SJ-6-1 and TE-25 will no longer intersect within the entire range of thrust-to-weight ratio variation.

This idea can be developed further. With equal start thrusts the cross-section area of the synergetic engine amounts to slightly more than 3/4 of that of the turbo-expander engine TE-25. If the turbo-compressor duct of the combined power plant is retained the same, then a 30 % more air could be bypassed around the frontal compressor of the synergetic engine. Such its variant, in other than that being similar to the version SJ-6-1, is called SJ-6-2. The air-flow matching coefficient k_q^* at the maximum Mach number and within the "transonic neck" will become equal to about 0.8 (see Table 6). The extrapolation of the data with respect to the parameter k_q^* allows obtaining the lower bound for the gain in fuel burn for acceleration equal to 20 % of the total fuel burn of the engine TE-25 or 2.2 -2.4 % of the vehicle start mass. The real saving in fuel is to be somewhat greater and in so doing the smaller will be the vehicle thrust-to-weight ratio the greater will be the gain as compared to the turbo-expander engine. It should also be borne in mind that in this case the decrease of the structural mass of the hypersonic vehicle associated with the decrease of the volume of its fuel tanks makes up approximately 0.3 - 0.4 % of the vehicle start mass and the total gain with constant structural mass of the engines will be no less than 2.5 - 2.8 %. Calculations of the characteristics of the variants SJ-6-1 and SJ-6-2 of the hypersonic synergetic air-breathing jet engine are to be performed in the coming time after having modified the mathematical model, the calculated results will be presented in the oral report which is to be the completion of handing over the information obtained under the contract.

It should be noted that the square cross section of the external duct is inherent in the version SJ-6. This being so, it becomes advisable to give up the walls of the external duct as a part of the engine itself and to use for this purpose the walls of the duct where the engine is located. This would be favorable for reducing the structural mass of the power plant and making easier the integration of the engine and airframe of the hypersonic vehicle. With the by-pass doors open, the turbo-compressor unit of the synergetic engine consisting of the frontal compressor and inverse-cycle module will be mounted on the pylons in the central portion of the power plant duct and the terminal combustion chamber of the external duct will be the structural part of the power plant as a whole rather than that of the turbo-compressor unit.

6. Preliminary estimates for the structural mass of the hypersonic synergetic air-breathing engine

The first objection of any expert for the author of the synergetic engine faced was that this engine will be more complex and heavier than the known power plants for hypersonic vehicles. As to the complexity, one can say that the time for simple solutions elapsed 20 - 30 years ago and at present nobody tries to employ simple and light-weight liquid-propellant rocket engines on sub- and supersonic aircraft instead of or in combination with complex and heavy turbojet engines, that was often the case within the period 1940 - 1960 beginning with rocket-powered aircraft BI-1, Messerschmitt-163, and X-1 and ending with Mirage-III and MiG-19, although at that time, too, this was mainly caused by the imperfection of the first models of turbojet engine. It should also be noted that the belief regarding the complexity of a synergetic engine is somewhat exaggerated because despite relatively large amount of its components they all, excluding the frontal compressor, operate in a practically single operating point (each in its own) and, after having this ensemble adjusted in start, one may no longer be careful that their operation in all flight regimes are well matched, which can not be the case even with a simplest turbojet engine.

As to the structural mass of a synergetic engine, here too, as estimates have shown, the situation is quite different from that believed by the experts who formulated their conclusions in the conditions inadequate to the new situation.

To substantiate this statement, let us consider the structural mass and some most important parameters of the variants SJ-5-7 and SJ-5-8 of the hypersonic synergetic engine and the turbo-expander power plant TE-25 with the same start thrust $P^o = 300$ kN. Consumption of propulsive mass and fuel, power and energy fluxes were obtained by calculating aerothermodynamic characteristics of the engine types being studied according to the second-level program [1]. The values of structural masses for separate units were calculated using correlation relationships [7] for sixth-generation engines and the expert-judgment method in collaboration with Ye. Tyurikov, CIAM consultant.

We begin with the turbo-expander engine to compare the calculated results with available data. Consider the version of the turbo-expander engine TE-25 designed without a gearbox due to the power on the shaft between the primary vapor turbine and (frontal) compressor being high at the start thrust $P^o = 300$ kN. The vapor turbine expansion ratio therewith is $\pi_{pt} = 5.16$, number of stages $z_{pt} = 13$ (only rotor stages without considering guiding device), hydrogen consumption $G_{pt} = 7.20$ kg/s at $M = 0$, power $N_{pt} = 38.4$ MW, turbine mass $m_{pt} = 460$ kg. In the framework of the computational model the compressor driven by this turbine has the same power and the air flow through it at $M = 0$ is $G_{fc} = 246$ kg/s, pressure ratio $\pi_{fc} = 3.5$, number of stages $z_{fc} = 1$, structural mass $m_{fc} =$ $= 240$ kg. Gas flow through the frontal combustion chamber is $G_{fb} = 249$ kg/s, heat power $N_{fb} = 405$ MW, structural mass $m_{fb} = 165$ kg. Hydrogen flow through the hydrogen-gas heat exchanger is equal to that through the primary vapor turbine (7.20 kg/s), gas flow is equal to that for the frontal combustion chamber (246 kg/s), heat flux power $N_{pe} = 122$ MW, mean logarithmic temperature differential is $\Delta T_L = 690$ K [8], heat-exchange area $S_{pe} = 160$ m^2, mass $m_{pe} = 160$ kg. Gas flow through the afterburning chamber is $G_{ab} = 253$ kg/s, heat power $N_{ab} = 538$ MW, structural mass including that of the subsonic portion of the nozzle $m_{ab} = 400$ kg. The turbopump assembly has the mass $m_p = 85$ kg; the total mass of shaft, supports, pipes, valves and other equipment is $m_e =$ $= 190$ kg. Thus, the structural mass of the turbo-expander engine without the casing amounts to $m_\Sigma^* = 1700$ kg and the specific weight is $\gamma^* = m_\Sigma^* g/P^o = 0.056$, which is in good agreement with the data known. The casing mass being equal to 300 kg, the total engine mass will be $m_\Sigma = 2000$ kg and its specific weight is $\gamma = 0.066$.

With the start thrust $P^o = 300$ kN, the variants SJ-5-7 and SJ-5-8 of the synergetic engine have the following mass and energy indices at $M = 0$: expansion ratio of the primary vapor turbine $\pi_{pt} = 5.25$, number of stages $z_{pt} = 13$, hydrogen flow $G_{pt} = 10.34$ kg/s at fuel consumption through all the combustion chambers $G_f = 5.47$ kg/s, power $N_{pt} = 58.0$ MW, turbine mass $m_{pt} = 180$ kg. Such a considerable reduction in the structural mass of the primary vapor turbine as compared to that of the turbo-expander engine at a significant growth of its power is associated with the fact that this unit has become substantially more harmonized. The increase of the power is mainly associated with the 1.4-fold increase of hydrogen flow passed through the turbine as compared to that of the TE-25 owing to the employment of the synergizer. The pressure at the entry to the turbine has increased by a factor of 2.5, its cross-section area decreased by a factor of 1.3 owing to a corresponding decrease in frontal compressor diameter, length reduced to a half as many due to the absence of the guiding device stages. The air flow through the frontal compressor is $G_{fc} = 187$ kg/s, its power $N_{fc} = 34.7$ MW, pressure ratio $\pi_{fc} = 4.25$, number of stages $z_{fc} = 2$, structural mass $m_{fc} = 160$ kg under conditions of being made of carbon-carbon composite.

Gas flow through the frontal combustion chamber is $G_{fb} = 101$ kg/s, heat power $N_{fb} = 163$ MW, with both the quantities being 2.5 times less than those for the turbo-expander engine at a slightly greater pressure owing to which its structural mass is $m_{fb} = 75$ kg. The power of the gas turbine is $N_{gt} = 29.1$ MW and mass $m_{gt} = 185$ kg.

The hydrogen flow through the hydrogen-gas heat exchanger is equal to that of the primary vapor turbine (10.34 kg/s), gas flow is the same as for the frontal combustion chamber (101 kg/s), the ratio of the former to the

latter became 3.5 times greater than that for the TE-25 engine. The heat flux power was slightly reduced (down to N_{pe} = 119 MW), mean logarithmic temperature differential decreased by a factor of 4 (down to ΔT_L = 170 K) at practically the same heat-transfer coefficient, according to estimates [8], because of this the heat-exchange area increased by a factor of 4 up to S_{pe} = 640 m^2. In this case the mass of the heat-exchanger must be m_{pe} = 640 kg. Such a considerable increase in structural mass is associated with the fact that the heat-exchanger of the synergetic engine is to ensure not only the heating of hydrogen but also a sufficiently deep cooling of the incoming gas flow, with these flows being balanced. In so doing the temperature differentials between gas and hydrogen are on the average decreased by a factor of 4. For the structural mass of the heat-exchanger of the synergetic engine not to increase so considerably, it is necessary to increase the heat-transfer coefficient between combustion products and the solid gas-flow interface which limits heat fluxes. For this to be done, one should provide that the mixing of the combustion products within the room between the tubes through which hydrogen is passed be efficient and with low losses, that will be favorable for increasing heat-transfer coefficient. The in-principle solution to the problem of many-fold intensifying the heat-exchange process under such conditions is found but for its refinement additional studies are needed. The associated proposals will be presented in the next section of the report. At present a reduction in heat-exchanger mass is assumed to be two-fold owing to heat-exchange intensification at the gas-solid wall interface, with the structural mass in this case being m_{pe} = 320 kg.

The pressure ratio of the terminal compressor is π_{tc} = 3.36, its number of stages z_{tc} = 1, power N_{tc} = 29.1 MW, structural mass m_{tc} = 80 kg. The pressure ratio of the booster compressor is π_{bc} = 2.08, its number of stages z_{bc} = 1, power N_{bc} = 23.3 MW, mass m_{bc} = 80 kg owing to greater operating temperature.

The gas flow in the afterburning combustion chamber is G_{ab} = 102 kg/s, heat power N_{ab} = 206 MW, the pressure is greater by a factor of 4.5 than that of the turbo-expander engine, because of this the structural mass together with the subsonic part of the nozzle when using advanced high-temperature alloys is only m_{ab} = 80 kg. The gas flow in the terminal combustion chamber G_{tb} = 86.3 kg/s, heat power N_{tb} = 307 MW, mass m_{tb} = 120 kg. However, the version SJ-6 of the synergetic engine has no casing of the terminal combustion chamber, its role being played by the walls of the gas-flow passage, where the engine is placed. In these conditions, m_{tb} = 50 kg. Shafts, supports, ducts, valves and other constituents of the synergetic engine taken together have significantly greater mass than in the case of the turbo-expander engine - m_e = 320 kg.

The heaviest element of the synergizer is the heat exchanger-regenerator. Its mass equals m_{er} = 55 kg, the heat flux power being N_{er} = 49.4 MW, which makes up 42 % of the heat power of the primary hydrogen-gas heat exchanger, since the minimum heat-transfer coefficient in this heat exchanger is by a factor of 2.5 greater than the corresponding parameter for the primary heat exchanger even after the intensification of the process. Thus, the use of the heat exchanger-regenerator allows decreasing the mass of the synergetic engine.

Power of the frontal vapor turbine N_{ft} = 15.3 MW, number of stages z_{ft} = 12, hydrogen flow through the turbine G_{ft} = 4.92 kg/s. Its mass m_{ft} = 20 kg, the structural mass of the rest of bladed units of the synergizer is from 20 to 25 kg. The total mass of the synergizer is m_s = 150 kg.

Thus, the structural mass of the synergetic engine without casing is estimated as m_Σ^* = 1750 kg including the walls of the terminal combustion chamber and 1680 kg with no such walls. Engine specific weight (engine structural weight referenced to the start thrust) γ^* = 0.055 - 0.057, which within accuracy of estimation coincides with that for the turbo-expander engine. The mass of the housing for the SJ-6 version of the synergetic engine must be less than that of the turbo-expander engine since the casing is basically associated with the internal duct, whose diameter is less by a factor of 1.6 - 1.7 than that of the TE-25 engine. However, pylons will be required for mounting the turbo-compressor unit in the duct of the power plant as well as controllable doors of the by-pass channel around the frontal compressor . Because of this, as a first approximation we assume that the total mass of these elements is the same 300 kg. In this case the total mass of the synergetic engine m_Σ = 1980 - 2050 kg, and γ = 0.065 - 0.067.

Undoubtedly, all these estimates of the mass of both the synergetic and turbo-expander engines are only a first approximations, the more so as the structural arrangement of the synerjet is still in development. However, the main conclusion from these estimates may no longer be revised: given an intensification of heat-transfer processes in the primary hydrogen-gas heat exchanger of the synergetic engine, the parameter γ does not practically differ from the analogous parameter of the optimum turbo-expander engine. In the case of using traditional heat exchangers, the parameter γ of the synergetic engine would be about 15 % greater.

Thus, the estimate of the lower bound of the start mass total diminution for the hypersonic vehicle in using the proposed synergetic air-breathing jet engine with an advanced heat exchanger presented at the end of the preceding section of this report and being equal to 2.5 % of the start mass is fully realistic. The use of a heat exchanger of common type decreases the gain by about 0.5 %.

7. Further research directions for advancing the concept

As appears from the previous sections of the present report, for finally establishing the concept of the synergetic air-breathing engine in complex with a hypersonic vehicle, it is still necessary to perform a number of studies. Besides, parallel versions of the power plants have been emerging, probably more efficient than the investigated ones. Furthermore, assessments performed on the basis of computed characteristics of the SJ-5 version of the synergetic engine show that such a device is a product of high technologies and in principle significantly exceeds the level of hypersonic turbo-compressor engines of the previous generation. This manifests itself in abrupt decrease of the power per thrust of thermal units of the synergetic engine, such as combustion chambers, and in abrupt increase of the power of machinery, such as turbines and compressors, as compared to the turbo-expander power plant - a typical representative of previous-generation engines. In the hypersonic synergetic engine, for mechanical units to operate, the resources of hydrogen as a source of chemical energy is used only through the frontal combustion chamber. In other, not so complex conditions, there is no fundamental problem to obtain mechanical energy using for this purpose all resources of fuel. For the SJ-5-7 and SJ-5-8 variants of the synergetic engine, the ratio of the power of the three compressor, placed in the gas passage and producing useful work on compressing the incoming flow, to the ideal heat power of the fuel being consumed in the frontal combustion chamber (the product of the fuel consumption and its specific heat of combustion) is equal to $\eta^* = 52$ %. This index is indicative of a higher fuel efficiency compared to known gas-turbine engines. Note that the corresponding efficiency index of the TE-25 variant of the turbo-expander engine is as low as 9 %. Thus, it is to be expected that general-purpose gas-turbine power plants with the core in the form the synergetic module can be created, which, using hydrogen as a fuel, will have higher efficiency compared to modern gas-turbine engines.

As a consequence of the aforesaid, the following plan is proposed of advancing the concept of the hypersonic synergetic engine and studying the application of synergism principles to other aerospace areas.

7.1 Investigation of the influence of air by-pass around the frontal compressor on the performance of the hypersonic synergetic engine (version SJ-6)

The SJ-6 version of the synergetic engine and its expected characteristics are described in sufficient detail in sections 5 and 6 of the present report. It is anticipated that the first results of this investigation will be presented in an oral report following completion of the contract.

7.2 Investigation of the performance of the hypersonic synergetic air-breathing engine with mixed flows of the internal and external ducts

All considered versions of the hypersonic synergetic engine have no mixing of flows of the internal and external ducts before the nozzle. A mixed-flow version of such a power plant is possible [3,5], where the flows are first mixed and then subjected to final operations of compression and heating before the nozzle entry (see Fig. 2(b)).

This version of the synergetic air-breathing engine can be intended to obtain moderate thrust ($P^o \geq 100$ kN). It differs from aforedescribed version in that it additionally has in the gas-flow passage adaptation compressor 53 placed behind primary hydrogen-gas heat exchanger 40, multi-lobe mixer 54 between compressors 53 and 41 and common combustion chamber 55 instead of afterburning combustion chamber 43 of the internal duct.

Adaptation compressor 53 increases the gas static pressure in the internal duct of the gas-flow passage to the pressure level in the external duct. Thereafter effective mixing of gas flows take place in a short and-light multi-lobe mixer. Next, fuel injection is performed into common afterburning combustion chamber 55 at a pressure about half as low as that in combustion chamber 43 of the previous versions of the engine, and the maximum pressure in the fuel line decreases. Because of this, all cross-sectional areas grow there, and the blade height of the first stages of vapor turbines, at which technological limits are not exceeded, can be reached either at a lower thrust of the engine or at its higher characteristics.

Therefore, it is advisable to modify the available mathematics model for designing mixed-flow synergetic engine and carry out a cycle of their investigations.

7.3 Optimization of characteristics of a hypersonic vehicle with the synergetic engine for maximum payload

The continuation of investigations described in section 5 of the present report is planned. The second phase of flight with a scramjet engine may be considered. Only in this way a variant of the synergetic engine may be selected which provides the optimization of the vehicle as a whole. In so doing, advanced hypersonic configuration

7. Further research directions for advancing the concept

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The continuation of investigations described in section 5 of the present report is planned. The second phase of flight with a scramjet engine may be considered. Only in this way a variant of the synergetic engine may be selected which provides the optimization of the vehicle as a whole. In so doing, advanced hypersonic configuration

can be used with significantly higher lift-to-drag ratio values at M > 6 and lower drag at transonic speeds than those of known configurations [9].

7.4 Refining of the mathematical model with allowance for changes of the effectiveness of the frontal compressor on the acceleration trajectory

In flying along the acceleration trajectory, the only bladed unit of the synergetic engine whose operating mode is not constant is the frontal compressor. In this case, its rotation speed may be somewhat changing, which can affect the power distribution between drums of the birotative primary vapor turbine and, through the turbine, the booster compressor. It is proposed to study this effect and, should the need arise, its elimination, and to take into account changes in the efficiency of the frontal compressor depending on its operating mode; to do this, a third-level mathematical model can be used [1].

7.5 The concept of a hypersonic acceleration-cruise synergetic air-breathing engine

So far the acceleration versions of the synergetic engine were considered not allowing wide changes of the thrust level. It is proposed to consider a version of the engine that would enable a decrease in the thrust needed for cruise after acceleration of the vehicle to the Mach number M = 5.5 - 6 at a cost of a some diminution of its acceleration characteristics.

7.6 The concept of a subsonic synergetic air-breathing engine

As already noted above, it is possible to create various gas-turbine liquid-hydrogen fueled power plants with the core in the form of a synergetic module, and it is expected, in accordance with some preliminary estimates, that such power plants should be more efficient than the plants known currently. The first such power plant can be a gas-turbine air-breathing engine for subsonic aircraft designed for cruise Mach numbers M = 0.75 - 0.85. It is anticipated that the proposed layout provides necessary throttling of the engine in transition from climb to cruise, and the specific impulse of such an engine at the same thrust loading would be 10 - 15 % higher than that of high-by-pass-ratio hydrogen-fueled turbojet engines.

7. 7 The concept of a supersonic synergetic air-breathing engine

It is proposed to assess the feasibility of a synergetic air-breathing engine for supersonic aircraft (flight cruise Mach number M = 2 - 2.5). The general arrangement of such an engine may not differ from that of the subsonic engine, but operating modes of its components will be completely different.

7.8 The concept of a single-duct hypersonic synergetic air-breathing engine for Mach number up to M = 12 - 15

So far the concept of a combined hypersonic power plant has been considered with two parallel ducts, one of them containing the synergetic air-breathing engine, and the other - a scramjet. As the concept of the synergetic engine is developed, it is more and more integrated with other components of the power plant. It is proposed to develop further the revealed trend and unite to a maximum degree the components of both engines in a single duct so that the scramjet part with supersonic combustion begins to operate from the start using the synergetic module placed before it as generator of supersonic flow. At the present time it is impossible to guarantee the creation of a fully practical system of such a type basically due to problems of matching air flows at transonic and hypersonic speeds, however, the possibility of considerably decreasing the structural mass of the power plant requires, in our opinion, a special investigation.

7.9 The concept of a solid-core synergetic nuclear rocket engine

It is proposed to use a synergetic gas-turbine unit for increasing the specific impulse of a solid-core nuclear rocket engine without raising the maximum temperature of its active zone. It is expected that the specific impulse of such an engine will increase from $(8.5 - 9)\cdot 10^3$ m/s to $(11 - 12)\cdot 10^3$ m/s, i.e., practically to the lower bound of values of specific impulse for gas-core nuclear rocket engines.

7.10 Numerical investigations of heat exchange intensification near solid surface due to stripping

Investigations have shown that the primary hydrogen-gas heat exchanger may turn out to be the heaviest unit of the synergetic air-breathing engine. Proposed in section 6 of the present report is a means of heat exchange intensification at the combustion products - solid surface boundary, which defines the heat transfer coefficient of this heat exchanger. It is proposed to conduct numerical study in the framework of the Navier-Stokes equation on the turbulent gas flow at Mach number $M \sim 0.1$ and Reynolds number $Re \sim 5 \cdot 10^4$ at about a cylindrical tube section with an axial-symmetric unit for heat-exchange intensification. The ANSYS/FLOTRAN code can be used to compute flows by the finite-element method [10]. As a result, necessary data may be obtained for determining the shape, size and number of the heat exchange intensification units together with the gain of intensification. Such a means of heat exchange intensification can be used in other heat exchangers as well, thus decreasing their sizes and masses.

We believe that it is advisable in the first place to carry out the five items of the proposed program, whose heading are printed in bold type. With proper efforts and funding, these items of the programs could be performed in one year, and it is advisable, taking into account the prospects for the topic, to carry out the work both by Russian and U.S. participants.

September 5, 1997

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Comparison of basic performance of the engines SJ-3 ÷ SJ-5 and TE-25
($R \cdot 10^{-3}$ and $I_{sp} \cdot 10^{-4}$ - m/c, T_{pt} - K, P/S and p_{max} - MPa)

Table 1

Type	π_{fc}^o	π_{pt}	T_{pt}^o	π_{ft}	π_{gt}	k_T	β_s^o	m_2
SJ-3-1	3.5	5.0	1125	5.5	2.5	1.00	1.00	1.00
SJ-3-2	4.0	5.0	1150	5.5	2.5	1.00	1.00	1.00
SJ-3-3	4.5	5.0	1275	5.5	2.5	1.00	1.00	1.00
SJ-4-1	3.5	5.0	1125	5.5	2.5	1.25	0.90	1.00
SJ-4-2	3.5	5.0	1275	5.5	2.5	1.10	0.80	1.00
SJ-4-3	3.5	5.0	1275	5.5	2.0	1.15	0.80	1.00
SJ-4-4	4.0	5.0	1275	5.5	2.5	1.10	0.90	1.00
SJ-4-5	4.0	5.0	1275	5.5	2.0	1.15	0.90	1.00
SJ-4-6	4.0	5.0	1275	5.5	1.875	1.175	0.90	1.00
SJ-4-7	4.0	5.0	1450	5.5	2.0	1.00	0.80	1.00
SJ-4-8	4.5	5.0	1450	5.5	2.0	1.00	0.90	1.00
SJ-5-1	4.0	5.25	1180	5.17	2.0	1.25	0.90	1.10
SJ-5-2	4.0	5.25	1180	4.99	2.0	1.25	0.90	1.10
SJ-5-3	4.0	5.25	1180	4.89	1.875	1.27	0.90	1.10
SJ-5-4	4.25	5.25	1240	4.99	1.875	1.20	0.90	1.10
SJ-5-5	4.5	5.25	1300	5.03	1.875	1.15	0.90	1.10
SJ-5-6	4.25	5.25	1240	4.98	1.875	1.20	0.90	1.10
SJ-5-7	4.25	5.25	1240	4.74	1.875	1.20	0.90	1.10
SJ-5-8	4.25	5.25	1240	4.74	1.875	1.20	0.90	1.10
SJ-5-9	4.10	5.00	1220	5.16	1.85	1.225	0.90	1.125
TE-25	3.5	5.34	1200	-	-	1.00	-	-

Table 2

M = 0.0

Type	R	I_{sp}	q(λ)	P/S	c_p	p_{max}	π_I	π_{II}	m_1	β_s
SJ-3-1	1.62	5.55	0.900	0.315	-	24.9	17.01	3.33	0.683	1.000
SJ-3-2	1.66	5.66	0.900	0.322	-	26.0	18.12	3.80	0.695	1.000
SJ-3-3	1.69	5.78	0.900	0.329	-	27.6	21.72	4.28	0.764	1.000
SJ-4-1	1.58	5.39	0.900	0.307	-	19.9	15.55	3.33	0.871	0.900
SJ-4-2	1.54	5.25	0.900	0.299	-	20.7	16.87	3.33	1.214	0.800
SJ-4-3	1.53	5.22	0.900	0.297	-	18.4	14.98	3.33	1.194	0.800
SJ-4-4	1.62	5.54	0.900	0.315	-	23.5	19.20	3.80	0.964	0.900
SJ-4-5	1.61	5.50	0.900	0.313	-	21.0	17.05	3.80	0.946	0.900
SJ-4-6	1.60	5.49	0.900	0.312	-	20.1	16.43	3.80	0.941	0.900
SJ-4-7	1.57	5.37	0.900	0.305	-	22.8	18.61	3.80	1.313	0.800
SJ-4-8	1.64	5.61	0.900	0.319	-	26.0	21.32	4.28	1.050	0.900
SJ-5-1	1.60	5.49	0.900	0.312	-	24.1	13.71	3.80	0.787	0.900
SJ-5-2	1.61	5.49	0.900	0.312	-	22.1	13.63	3.80	0.784	0.900
SJ-5-3	1.60	5.48	0.900	0.312	-	21.2	13.19	3.80	0.780	0.900
SJ-5-4	1.62	5.55	0.900	0.315	-	23.8	14.38	4.04	0.815	0.900
SJ-5-5	1.64	5.61	0.900	0.319	-	26.1	15.64	4.28	0.849	0.900
SJ-5-6	1.62	5.55	0.900	0.315	-	23.7	14.38	4.04	0.815	0.900
SJ-5-7	1.60	5.49	0.900	0.312	-	20.8	13.24	4.04	0.856	0.900
SJ-5-8	1.60	5.49	0.900	0.312	-	20.8	13.24	4.04	0.856	0.900
SJ-5-9	1.59	5.43	0.900	0.309	-	20.1	12.08	3.90	0.818	0.900
TE-25	1.22	4.17	0.900	0.237	-	1.62	-	2.93	-	-

Table 3

M = 1.2

Type	R	I_{sp}	$q(\lambda)$	P/S	c_p	p_{max}	π_I	π_{II}	m_1	β_s
SJ-3-1	1.52	5.21	0.862	0.290	6.95	24.4	15.66	3.07	0.683	0.998
SJ-3-2	1.54	5.28	0.856	0.292	7.00	25.3	16.56	3.48	0.695	0.998
SJ-3-3	1.56	5.35	0.851	0.294	7.05	26.7	19.75	3.89	0.764	0.998
SJ-4-1	1.52	5.19	0.914	0.306	7.34	21.8	16.07	3.40	0.871	0.918
SJ-4-2	1.49	5.10	0.917	0.302	7.25	22.8	17.57	3.42	1.214	0.819
SJ-4-3	1.48	5.08	0.916	0.300	7.20	20.3	15.56	3.41	1.194	0.817
SJ-4-4	1.54	5.28	0.919	0.314	7.52	26.0	20.03	3.92	0.964	0.921
SJ-4-5	1.54	5.25	0.917	0.311	7.46	23.1	17.72	3.91	0.946	0.918
SJ-4-6	1.53	5.25	0.917	0.311	7.45	22.1	17.09	3.91	0.941	0.918
SJ-4-7	1.48	5.07	0.856	0.281	6.73	22.1	17.02	3.48	1.313	0.798
SJ-4-8	1.53	5.24	0.851	0.288	6.90	25.0	19.38	3.89	1.050	0.898
SJ-5-1	1.53	5.25	0.916	0.311	7.44	26.5	14.20	3.90	0.787	0.918
SJ-5-2	1.54	5.27	0.928	0.316	7.57	24.9	14.44	3.98	0.784	0.922
SJ-5-3	1.54	5.26	0.928	0.316	7.57	23.8	14.00	3.98	0.780	0.921
SJ-5-4	1.55	5.30	0.930	0.319	7.63	26.8	15.27	4.24	0.815	0.921
SJ-5-5	1.56	5.34	0.929	0.320	7.68	29.2	16.54	4.48	0.849	0.921
SJ-5-6	1.55	5.30	0.930	0.319	7.63	26.7	15.27	4.24	0.815	0.921
SJ-5-7	1.54	5.26	0.930	0.316	7.58	23.4	14.07	4.24	0.856	0.922
SJ-5-8	1.54	5.26	0.930	0.316	7.58	23.4	14.07	4.24	0.856	0.922
SJ-5-9	1.53	5.23	0.929	0.314	7.52	22.6	12.82	4.14	0.818	0.922
TE-25	1.24	4.26	0.870	0.239	5.74	1.59	-	2.70	-	-

Table 4

M = 3.0

Type	R	I_{sp}	$q(\lambda)$	P/S	c_p	p_{max}	π_I	π_{II}	m_1	β_s
SJ-3-1	1.45	4.95	0.719	0.338	6.77	29.4	9.24	1.82	0.683	0.975
SJ-3-2	1.45	4.97	0.679	0.320	6.41	29.0	9.29	1.96	0.695	0.975
SJ-3-3	1.46	4.99	0.646	0.306	6.12	29.3	10.59	2.10	0.764	0.975
SJ-4-1	1.46	5.00	0.761	0.361	7.23	30.1	10.87	2.27	0.815	0.966
SJ-4-2	1.44	4.93	0.719	0.337	6.73	28.0	10.56	2.07	1.064	0.861
SJ-4-3	1.44	4.93	0.731	0.342	6.84	26.1	9.81	2.15	1.056	0.868
SJ-4-4	1.46	4.98	0.694	0.328	6.56	29.8	11.20	2.20	0.895	0.936
SJ-4-5	1.45	4.98	0.707	0.334	6.69	27.9	10.44	2.30	0.885	0.945
SJ-4-6	1.46	4.98	0.714	0.338	6.76	27.4	10.35	2.35	0.877	0.952
SJ-4-7	1.44	4.91	0.660	0.308	6.16	26.7	10.06	2.07	1.123	0.847
SJ-4-8	1.45	4.96	0.636	0.300	6.00	28.4	10.76	2.18	0.946	0.922
SJ-5-1	1.46	5.01	0.735	0.350	7.00	35.2	9.25	2.51	0.732	0.965
SJ-5-2	1.47	5.01	0.735	0.350	7.01	32.3	9.18	2,51	0.729	0.965
SJ-5-3	1.47	5.02	0.741	0.353	7.07	31.5	9.06	2.55	0.728	0.967
SJ-5-4	1.46	5.01	0.708	0.337	6.73	32.6	9.10	2.51	0.752	0.958
SJ-5-5	1.46	5.00	0.680	0.323	6.47	33.3	9.22	2.49	0.785	0.946
SJ-5-6	1.40	5.18	0.757	0.346	6.92	33.8	9.45	2.61	0.804	1.000
SJ-5-7	1.40	5.15	0.757	0.344	6.89	29.6	8.70	2.61	0.846	1.000
SJ-5-8	1.40	5.15	0.759	0.345	6.90	29.6	8.70	2.61	0.851	1.000
SJ-5-9	1.40	5.13	0.771	0.351	7.01	29.5	8.18	2.59	0.814	1.000
TE-25	1.29	4.43	0.660	0.278	5.55	1.92	-	1.60	-	-

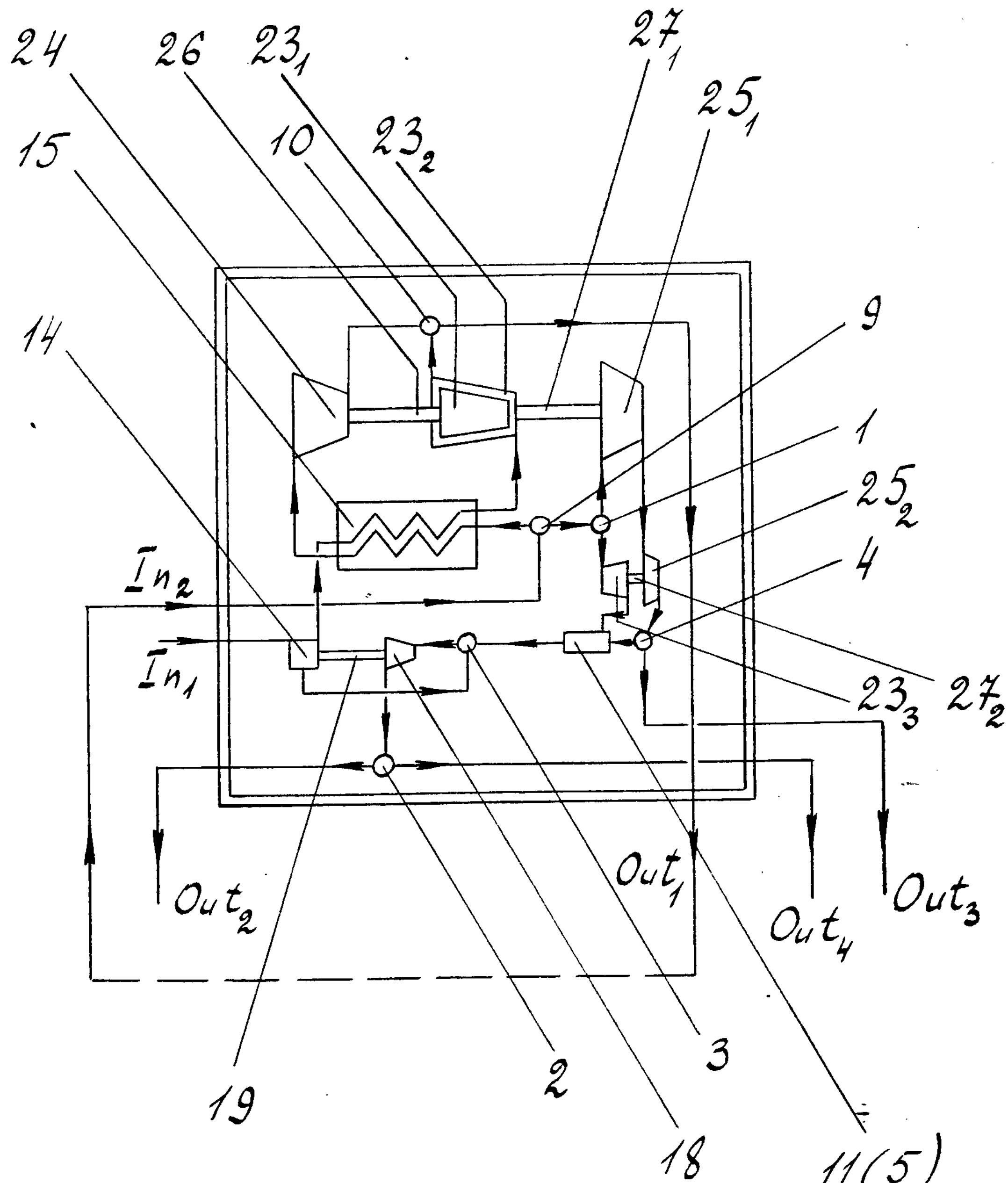
Table 5

M = 5.5

Type	R	I_{sp}	q(λ)	P/S	c_p	p_{max}	π_I	π_{II}	m_1	β_s
SJ-3-1	1.18	4.02	0.801	0.544	10.87	54.6	6.16	1.24	0.683	0.899
SJ-3-2	1.17	4.02	0.724	0.491	9.83	51.7	5.94	1.28	0.695	0.898
SJ-3-3	1.18	4.02	0.663	0.450	9.00	50.2	6.49	1.32	0.764	0.898
SJ-4-1	1.18	4.04	0.693	0.473	9.46	51.6	6.64	1.42	0.609	1.000
SJ-4-2	1.18	4.05	0.637	0.435	8.70	52.4	7.04	1.42	0.628	1.000
SJ-4-3	1.18	4.03	0.639	0.435	8.70	47.8	6.40	1.44	0.632	1.000
SJ-4-4	1.18	4.05	0.629	0.430	8.59	52.3	7.03	1.42	0.627	1.000
SJ-4-5	1.18	4.03	0.630	0.430	8.59	47.8	6.38	1.44	0.632	1.000
SJ-4-6	1.18	4.03	0.632	0.430	8.60	46.2	6.22	1.46	0.638	1.000
SJ-4-7	1.18	4.04	0.577	0.393	7.86	50.1	6.72	1.43	0.644	1.000
SJ-4-8	1.18	4.04	0.574	0.391	7.82	50.4	6.80	1.42	0.645	1.000
SJ-5-1	1.18	4.04	0.635	0.433	8.66	57.3	5.37	1.49	0.530	1.000
SJ-5-2	1.18	4.04	0.635	0.434	8.67	52.6	5.34	1.49	0.528	1.000
SJ-5-3	1.18	4.04	0.636	0.434	8.68	50.8	5.21	1.51	0.530	1.000
SJ-5-4	1.18	4.04	0.608	0.415	8.29	53.2	5.30	1.50	0.535	1.000
SJ-5-5	1.18	4.04	0.582	0.397	7.94	54.8	5.41	1.50	0.545	1.000
SJ-5-6	1.18	4.04	0.608	0.415	8.29	53.1	5.30	1.50	0.535	1.000
SJ-5-7	1.17	4.02	0.608	0.413	8.25	46.5	4.88	1.50	0.573	1.000
SJ-5-8	1.17	4.02	0.608	0.413	8.25	46.5	4.88	1.50	0.573	1.000
SJ-5-9	1.17	4.01	0.624	0.423	8.45	46.7	4.61	1.49	0.549	1.000
TE-25	1.07	3.67	0.465	0.288	5.76	3.67	-	1.09	-	-

Table 6

Type	$q_3(\lambda)$	$q_5(\lambda)$	$k_q=q_3/q_5$	k_q^*
SJ-3-1	0.862	0.801	0.929	1.74
SJ-3-2	0.856	0.724	0.846	1.58
SJ-3-3	0.851	0.663	0.779	1.46
SJ-4-1	0.914	0.693	0.758	1.42
SJ-4-2	0.917	0.637	0.695	1.30
SJ-4-3	0.916	0.639	0.698	1.31
SJ-4-4	0.919	0.629	0.684	1.28
SJ-4-5	0.917	0.630	0.687	1.29
SJ-4-6	0.917	0.632	0.689	1.29
SJ-4-7	0.856	0.577	0.674	1.26
SJ-4-8	0.851	0.574	0.675	1.26
SJ-5-1	0.916	0.635	0.693	1.30
SJ-5-2	0.928	0.635	0.684	1.28
SJ-5-3	0.928	0.636	0.685	1.28
SJ-5-4	0.930	0.608	0.654	1.22
SJ-5-5	0.929	0.582	0.626	1.17
SJ-5-6	0.930	0.608	0.654	1.22
SJ-5-7	0.930	0.608	0.654	1.22
SJ-5-8	0.930	0.608	0.654	1.22
SJ-5-9	0.929	0.624	0.672	1.26
SJ-6-1	-	-	-	~1.0
SJ-6-2	-	-	-	~0.8
TE-25	0.870	0.465	0.534	1.00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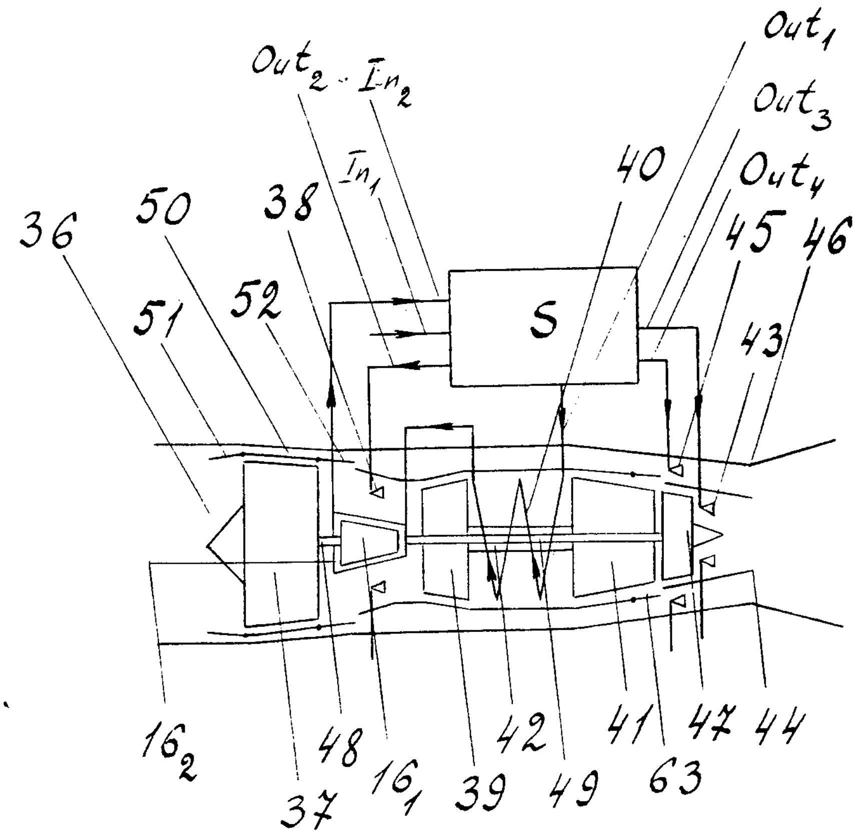
Out_4
Out_3
19
2
3
18
11(5)

Fig. 1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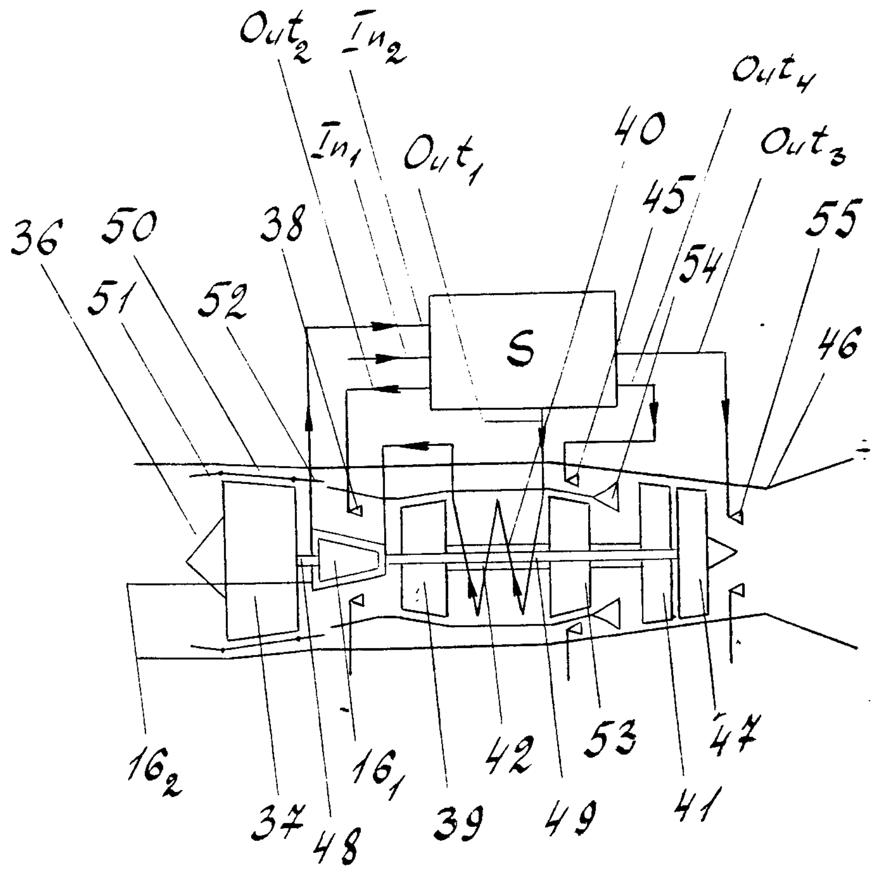
63

a)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16_1
39
49
41

б)

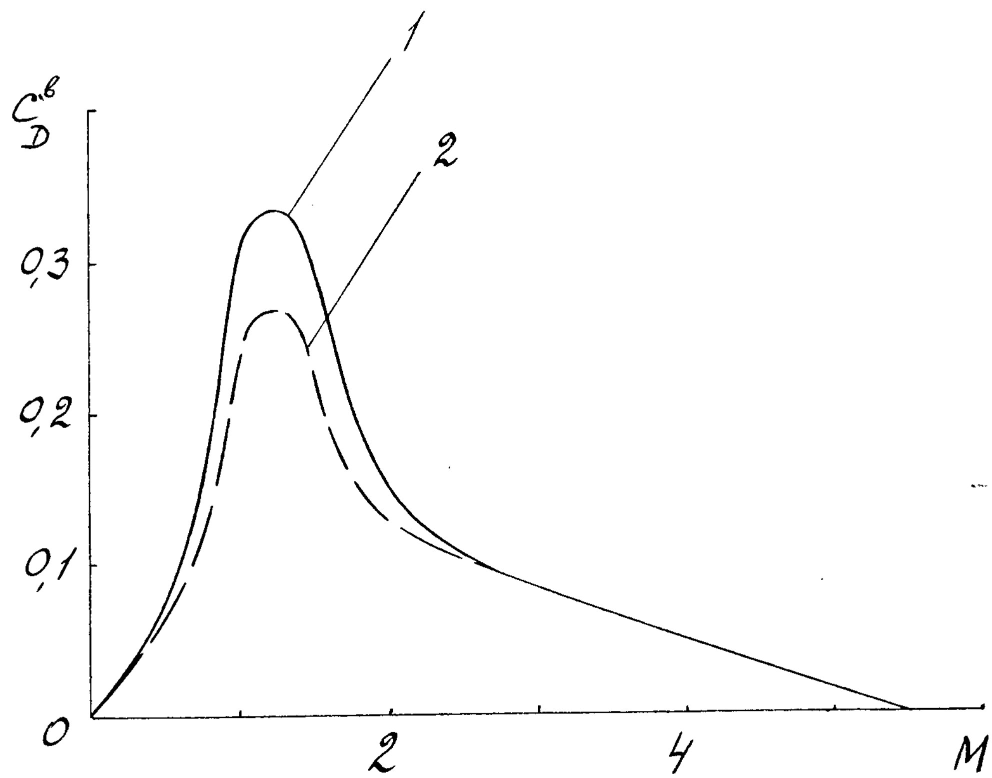
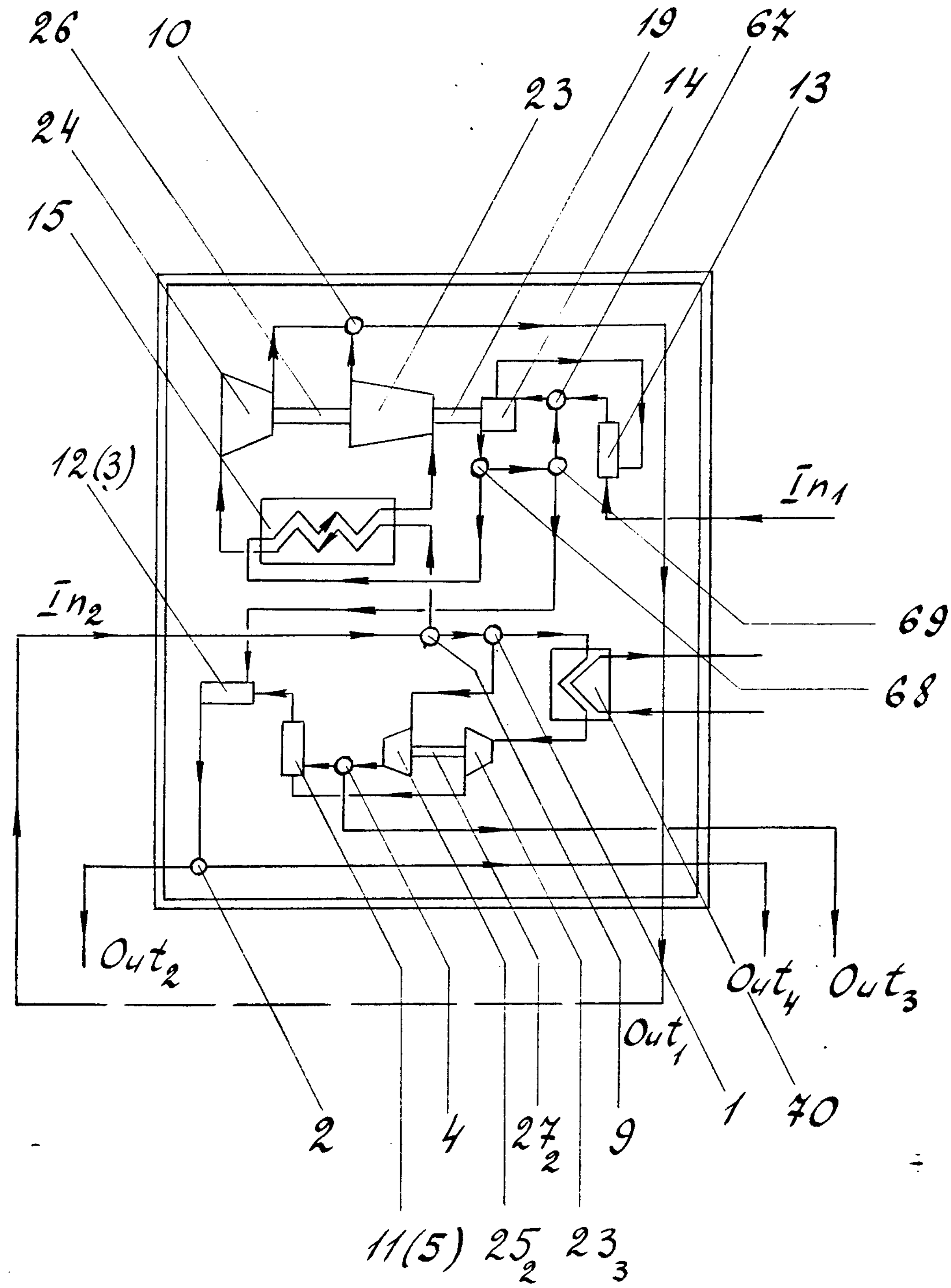


Fig. 3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In2
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Out2
Out4
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2
4
272
9
1
70
11(5)
252
233

Fig. 4

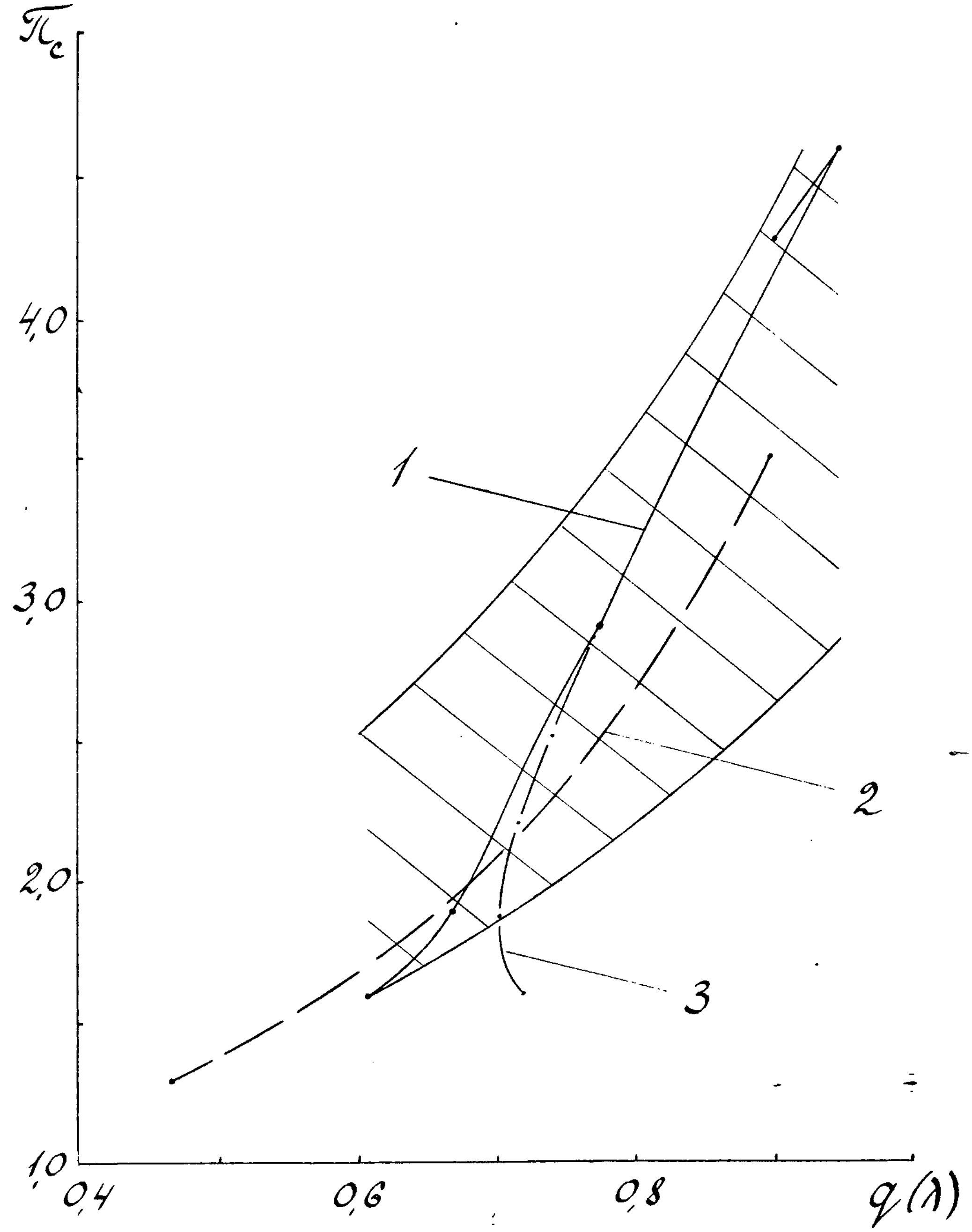
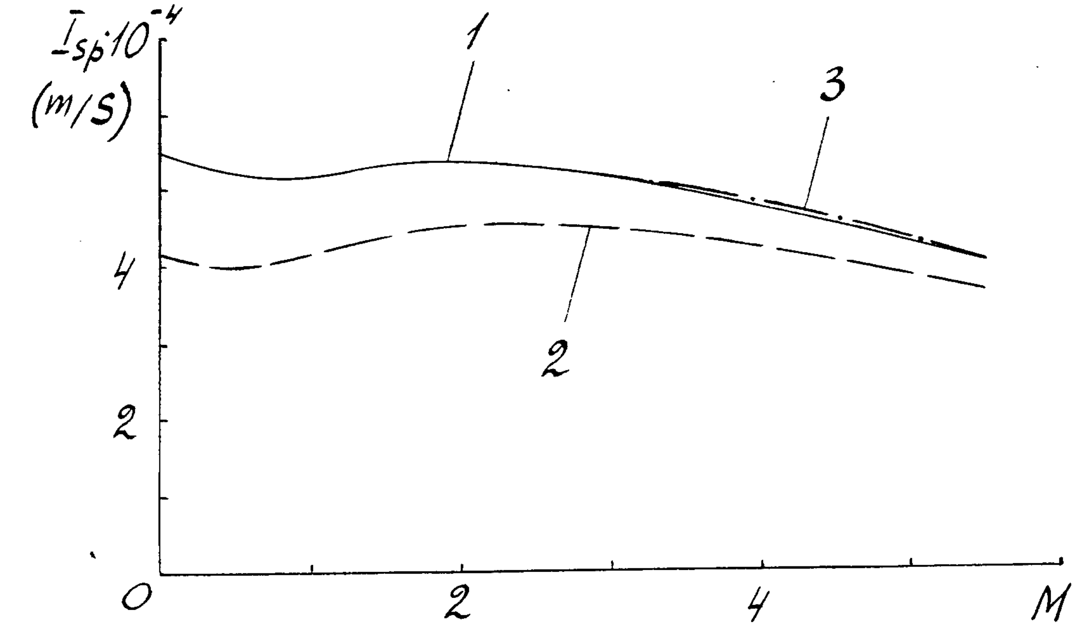


Fig. 5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(m/s)
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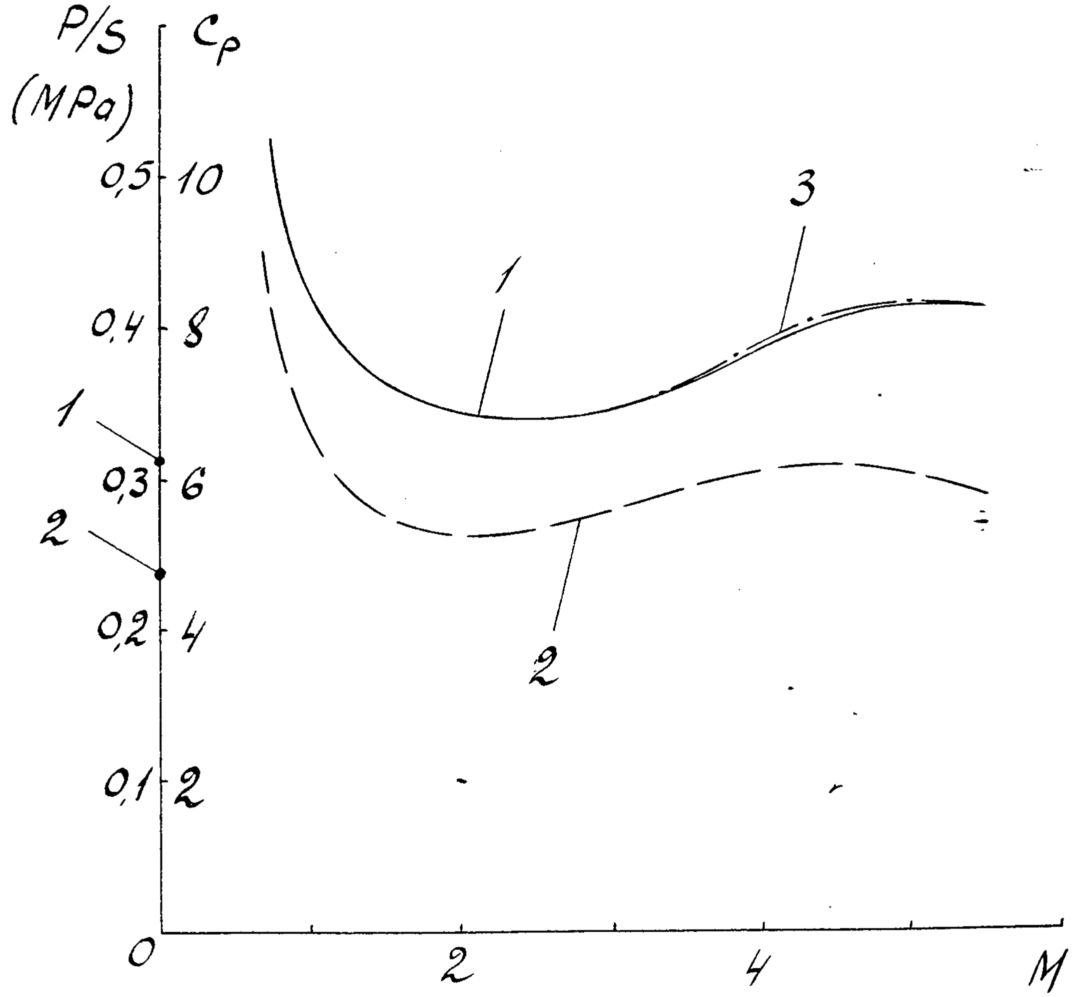
3
2
4
2
0
2
4
M

a)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(MPa)
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3
1
2
0
2
4
M

b)

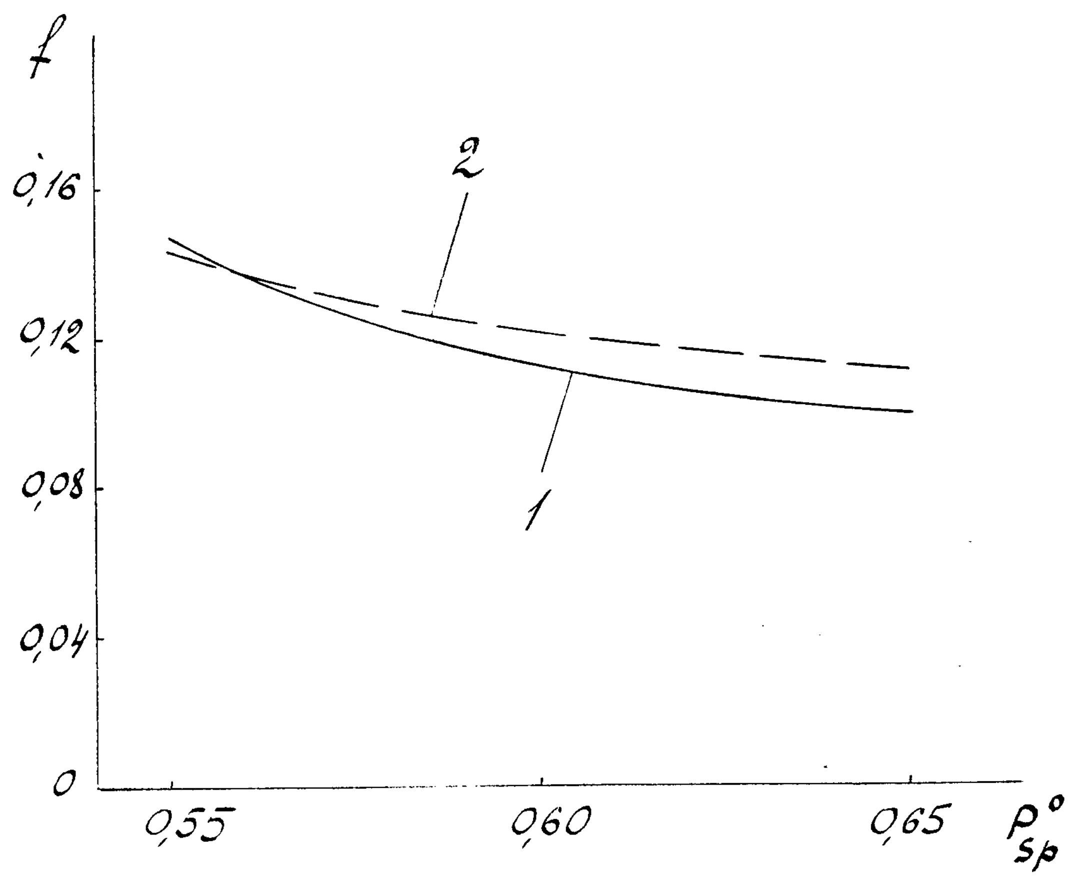

Fig. 7